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Implementing and Testing of Industrial PLC Units in the Electric Formula Student Racer

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This Bachelor's thesis was done with the intention to increase the understanding of the electric and dynamic systems in the electric Formula Student racer HPF015 built by Metropolia Motorsport in 2015. Due to a significant number of electrical parts being transferred to the new competing car, a new control system design had to take place to keep the car as a testing platform for the team.

Due to issues with the electrical system in HPF015, enough data for the design of the new car was not achieved. The same issue had taken place for approximately three full seasons. The lack of data has been considered as one of the key issues resulting in repeated failures and difficulty of troubleshooting the electrical system. For this reason, a rugged testing platform was necessary to be made with the intention to understand all the aspects of the behaviour in both electric and dynamic systems of the car, before the design of HPF017 was to be started.

The system design is based on ABB AC500 – XC series units. AC500 - XC is a PLC platform designed for harsh industrial environments. With combining the robustness of an automotive system, the high processor power and an extraordinary data logging capability the system fulfils the requirements easily. Also testing this type of system in an electric car was considered interesting by ABB Oy, therefore the necessary components were sponsored by the company for this project.

The main targets of the design were to implement the industrial PLC system into a Formula Student car, gather a significant amount of data during the short track time and giving a possibility of further testing possibilities if the team decides to continue with a similar type of car. Due to the structure of the system, expanding the data logging is possible by adding components to the ProfiNet network. As the load of data read in is only about 14 % in analogue data and even less in data buses, the possibilities can be considered almost limitless for this type of application. The expansion possibility is neither restricted to manufacturer due to the use of an industrially standardized data bus.

Keywords	Formula SAE, Formula Student Electric, AC500 XC

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List of abbreviations

FS	*Formula Student*
FSE	*Formula Student Electric*
HPF	*Helsinki Polytechnic Formula*
Helsinki Metropolia UAS	*Helsinki Metropolia University of Applied Sciences*
IMechE	*Institution of Mechanical Engineers*
SAE	*Society of Automotive Engineering*
ABB	*Asea Brown Boveri*
PLC	*Programmable Logic Controller*
CS	*Control System, control of all systems*
GLV	*Ground Low Voltage (referring to all systems < 60V)*
HV	*High Voltage (referring to voltages > 60 V)*
TS	*Tractive System*
CAN	*Controller Area Network*
ProfiNet	*Process Field Net*
XC	*eXtreme Conditions*
VCU	*Vehicle Control Unit*
IMD	*Insulation Monitoring Device*
AIR	*Accumulator Isolation Relay*
CRC	*Cyclic Redundancy Check*
ISOspi	*Isolated Serial Peripheral Interface*
Powerbud	*Aluminium high voltage conductor made for electric car applications*
PCB	*Printed Circuit Board*
HVSPADU	*High Voltage System Protection and Distribution Unit*
SC	*Shutdown Circuit*

PMSM	*Permanent Magnet Synchronous Motor*
ESF	*Electrical Safety Form*
I/O	*Input/Output*
RTDM	*Ready To Drive Mode*
RTDS	*Ready To Drive Sound*
TSAL	*Tractive System Active Light*
IEEE	*Institute of Electrical and Electronics Engineers*
TCP	*Transimission Control Protocol*
IP	*Internet Protocol*
IRT	*Isochronous Real Time*
COTS	*Commercial Off The Shelf*
Mil Spec	*Military Specification*
CAD	*Computer Aided Design*
EMI	*Electromagnetic Interference*
CPU	*Central Processing Unit*
SOF	*Start Of Frame*
RTR	*Remote Transmission Request*
IDE	*Identifier Extension*
DLC	*Data Length Code*
EOF	*End Of Frame*
CBA	*Component Based Automation*
PNO	*PROFIBUS Nutzerorganisation*
OSI	*Open Systems Interconnection*
ISO	*International Standardization Organization*
MAC	*Medium Access Control*
OUI	*Organizationally Unique Identifier*
UDP	*User Datagram Protocol*
PE	*Protective Earth*

Energy Meter	*Device for measuring energy consumption during the competition events*
IL	*Instruction List*
ST	*Structured Text*
LD	*Ladder Diagram*
FBD	*Function Block Diagram*
SFC	*Sequential Function Chart*
UI	*User Interface*
FTP	*File Transfer Protocol*
IC	*Integrated Circuit*

1 Introduction

A Programmable Logic Controller (*PLC*) is most often placed on any modern vehicle, which utilizes the benefits of an electrical system. However, it is a necessity on a vehicle which is expected to have adequate efficiency. In this thesis two very different fields are combined: Industrial systems will be merged into racing applications with the intention to test how they collaborate in harsh environments.

As electric cars are becoming more common they need control systems for both prototyping and serial manufacturing. Many automotive manufacturers have designed their own devices for commercial use. The devices in private trade however, are not too affordable. They also tend to have a set amount of data inputs that cannot be easily extended.

The vision behind this thesis was to enable the possibility to use industrial PLC technology in electric vehicles. The project was implemented on a former Formula Student Electric car as a secondary development project for Metropolia Motorsport ry. The fundamental design, however, could be applied to a various range of vehicles due to its expandability.

1.1 Formula Student Electric

In the early 1980's automotive companies had a mutual issue. Young engineers graduating from universities did not obtain enough hands on experience in automotive design. This led to the founding of Formula SAE in 1981. The original objective of the series was to increase students' competence in automotive design during their studies.
[1]

After showing its potential, Formula SAE was brought to Europe in 1998 for a demonstration event run by Institution of Mechanical Engineers (*IMechE*). Since then the competition series have spread throughout the world with different names. In 2010 Formula Student Electric (*FSE*) emerged from the series. It is a competition between fully electric vehicles. FSE vehicles compete at the same events as combustion powered cars with slightly modified rules. The difference can be found mainly in safety concerning entireties, the electrical system operations and energy consumption scoring.
[1]

1.2 Metropolia Motorsport ry

Founded in the year 2000, Metropolia Motorsport ry is one of the oldest European teams competing in Formula Student. The team was originally known as Stadia Motorsport according to the university name. The name was changed in 2011 when the team became a registered association. During the season in 2015, the team built their 13th car. At the moment, the team headquarters is located in the Helsinki Metropolia University of Applied Sciences (*Helsinki Metropolia UAS*) Automotive campus in the centre of Helsinki.
[2]

The team consists typically of eight active members and additional ten part-time members. The actions of the team are strictly controlled by a board of five. Prominent resources are provided by Helsinki Metropolia UAS and multiple companies for building the car and competing internationally. More than 40 companies are involved in providing materials and services for manufacturing the car annually.

Until 2011 the team only built combustion powered vehicles. After the FSE was started Metropolia Motorsport begun the development of an electric car and left the combustion powered cars to history. The first electric car was completed in 2013. The second season 2014 was a failure due to issues with a foreign inverter manufacturer. This played a role in the team's motivation for starting the next season 2015.
[2]

1.3 Helsinki Polytechnic Formula 2015

Derived from the original name of HMUAS (*Helsinki Polytechnic Stadia until 2008*) the HPF015 is the 3rd fully electric car designed and manufactured by Metropolia Motorsport. The car was taken from an early design state to testing according to a strict FS schedule of less than eight months. The team attended competitions in United Kingdom, Germany, Austria and Hungary. HPF015 won the efficiency section twice, however, was not able to execute proper dynamic performance.

Due to electrical issues during the seasons 2013-2014, HPF015 was simplified as much as possible and can even be considered austere in its design. The original design of the car was simplified for understanding the fundamentals of automotive design. The main design criteria were good functionality, a service friendly structure and decent dynamic properties. Finally there were a couple key issues that restricted the car's dynamic performance in the competitions.

HPF015 is an electric rear wheel driven car. Weighing 238 kg with a power output of 64 kW on the drive shafts it is a very fast accelerating agile car made for speeds up to 120 km/h. In principle the design is very simple. It comprises a hybrid steel tube frame with structural side and floor panels, aerodynamics consists of a front and a rear wing paired with a umderbody, a double wishbone suspension with multiple settings, a battery with a nominal voltage of 518 V and a maximum capacity of 6, 63 kWh, two electric motors one for each rear wheel paired with an industrial inverter and a control system utilizing automotive controllers. The result is a very simple car with high track potential.
[3, p. 1, 3]

Figure 1. HPF015 on in Autocross event in Formula Student Germany

1.4 Motivation for executing this project

The original objective of this thesis was to acquire a deeper understanding of the electric and dynamic behavior of the HPF015. During the competition season the car had several electrical malfunctions, and some of them were very difficult to troubleshoot.

The car had three separate Controller Area Networks (*CAN*), which operate in different systems. Practically, it means that one of them was connected to the data logger, one to the inverters and one only for parametrizing the accumulator. There were several situations where the data would have needed to be aligned on the same time axis for analysis. This was very difficult to put into practice and therefore caused occasions where the data was analyzed incorrectly. Setting up different systems also required physical connections to different CAN networks.

As the car uses a MoTeC ADL-8 with only 8 MB of memory it runs out of it quite fast (*Chapter 4.2.2 Calculations*). It is only capable of logging one CAN bus at the time and only use six different CAN addresses. Due to the physical separation, the data was very difficult to align in the same time axis and resulted in several misconceptions. This had a significant impact on understanding different issues at hand.
[4, p. 9]

One of the main criteria for this thesis was to unite the electrical system in a way that all systems were accessible. The possibility of logging several systems at once was also highly prioritized for improving the efficiency of troubleshooting.

2 Framing of Bachelor's thesis

Since this thesis has a wide platform to work with, it is considered that a proper framing is required. This is done for the reader, to properly understand the outcome and success of the thesis. This framing contains the main goals, which are considered to be a prerequisite for a successful thesis.

2.1 Premise

The project will start with an electric car with stripped electrical systems; this regards only the Control System. The main components such as an accumulator, inverters and electrical motors are only slightly altered in this work. Some modifications are made for data logging purposes, interference suppression and for fitting the old system to the new one mechanically. Some corrections for old flaws will be done to assure proper function of the full system. However, to keep the thesis as short as possible, all details will not be addressed.

2.2 Objectives

The main design objectives of this thesis are the following: Electric system design with a consideration of all electrical components needed, necessary calculations done and proper documentation for the design work to be created. The wiring harness will be looked at, as a separate component due to its environmental requirements. The design of a wiring harness and proper documentation in a readable way is also considered important.

The manufacturing of mechanical mountings, housings and harness are included in the thesis. As the CS will be quite extensive with data logging capabilities it will technically be possible to make various dynamic functions. This, however, will not be considered necessary for finalizing the project. All most basic functions must still work, these functions focus on the safety of the driver (*Chapter 4.1 System requirements*).

The last part of the project goal is to test the car on track. This will be done to ensure the functionality when driving. Additionally, a test drive with most of data logging in use will be made for approximately 20 km to prove the system functionality. Most of data logging in use refers to all sensors logged. An exception, however, is made considering some temperature measurements and some inverter data that are not critical.

3 Introduction of existing electrical system of HPF015

This chapter will give a short introduction to the existing electrical system of HPF015. Renderings and the data introduced in this chapter are borrowed from the 2015 Electrical Safety Form (*ESF*) made for the competitions. It is shown only with the purpose to clarify what the PLC system operates with, and has not been created by the author of this Bachelor's thesis.

3.1 Accumulator

The accumulator is defined as an energy unit in an electric car. This unit incorporates both battery cells and the systems regarding its functional safety and will be referred to as an accumulator when discussed as a whole unit.

The battery consists of 280 cells with a 140 S 2 P layout. They give out a nominal voltage of 518 V and 6, 63 kWh of capacity. The cells are mounted in an aluminium housing which contains all contributory systems. The housing is divided into five cell stacks and an accumulator control system section.
[3, p. 11]

The housing is insulated with polyamide plastic which possesses a dielectric strength of 30 kV and a flammability rating of UL 94 – V0. The mechanical layout is designed to withstand 40 g of lateral and longitudinal acceleration and 20 g vertical acceleration.
[5, p. 104-105]

The battery cells are used for supplying the GLV system. The conversion to 12 V is done by a DC/DC converter which is connected to three out of five stacks. Unfortunately, this causes the battery cells to drain into imbalance. The DC/DC converter was originally taken from an older accumulator unit and it cannot handle more than 450 VDC. Additionally, the inverters are supplied with 24 VDC using a separate DC/DC.

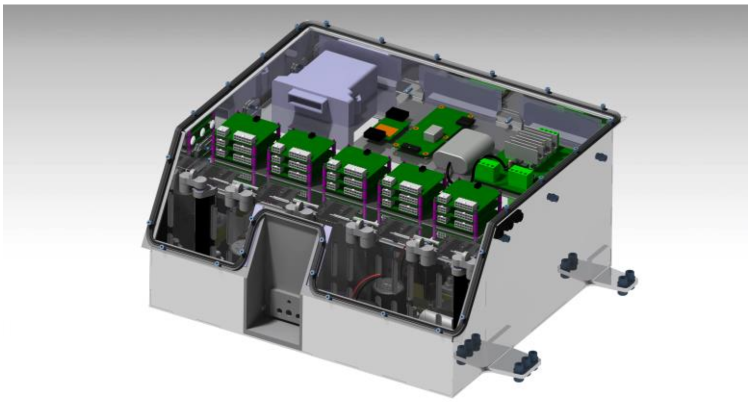

Figure 2. Mechanical layout of accumulator

3.1.1 Battery cells

The cells used are Lithium-ion Polymer type pouch bag cells. They have a capacity of 6, 40 Ah and nominal voltage of 3, 70 V. The cells are laid in five stacks, each with 28 S 2 P layout. Every stack's maximum energy is restricted to 6 MJ by the FS rules. The cell stacks can be separated without tools for maintenance.
[6, p. 2]

Figure 3. Battery cell assembly and housing

3.1.2 High voltage paths and control

Cells are connected to each other by rivets. The high voltage path is made out of aluminium conductors connected by either bolted connections or Powerbuds. The AIR's are connected to the high voltage path and controlled by the AMS. Outside of the accumulator a high voltage cable is lead to the High Voltage System Protection and Distribution Unit (*HVSPADU*). Inside the HVSPADU, all conductors are made of aluminium.

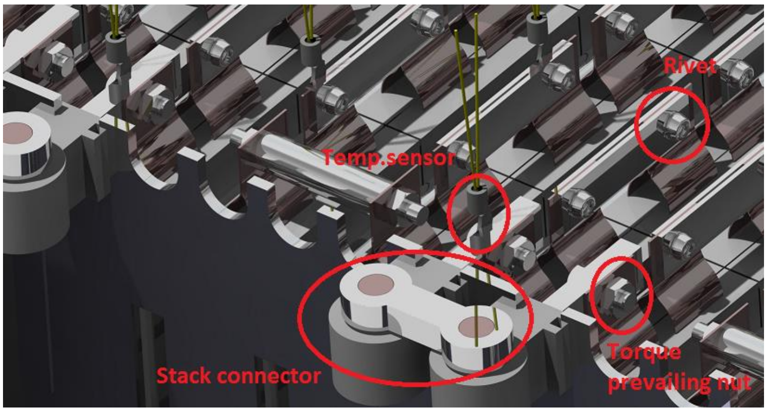

Figure 4. High voltage path

3.1.3 Accumulator Management System

A distributed type of AMS is used in HPF015. The system includes one AMS master unit and fifteen AMS slave units. Each stack is connected to three slave modules which read the cell temperature and voltages. The layout is 12+12+4 voltage measurements (max 12 in one slave unit) and 15 temperature measurements (max 5 in one slave unit) for each stack. The cell data is transferred to the CAN bus via the AMS master unit. A Cyclic Redundancy Check (*CRC*) fault value counter and balancing data is also transferred to the user via CAN for data logging purposes.

The slave units are designed by the team but are so similar to the evaluation Printed Circuit Board (*PCB*) by Linear Technologies, that it is considered appropriate to utilize its datasheet to clarify the system layout.

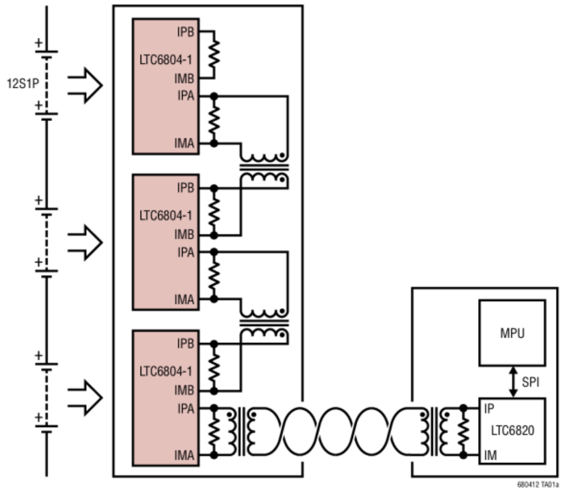

Figure 5. ISOspi daisy chain configuration

The master unit is a prototyping device manufactured by Valmet Automotive Oy. The device controls the slave units balancing feature and request data from the ISOspi bus. Slave units are connected to the master unit in a daisy chain configuration.

The AMS controls the Accumulator Isolation Relays (*AIRs*) based on the cell data and high level control from CAN. The AMS is equipped with a power stage for driving a relay that closes the Safety Circuit (*SC*). Some I/O channels are used for controlling the charging process. Parametrizing is done by a separate CAN bus. The system is referred to as AMS due to its features beyond accumulator voltage and temperature monitoring.

3.1.4 Insulation Monitoring Device

The High Voltage (*HV*) system is galvanically separated from the CS to protect the driver from the high Direct Current (*DC*) voltage. Bender 3204 is a device capable of monitoring the insulation resistance between the insulated active HV conductors and the reference earth used in the CS. It uses a response value of approximately 500 Ω / V. The insulation resistance value is set to be 300 kΩ.The Insulation Monitoring Device (*IMD*) is connected to the car’s SC and is capable of opening the HV-circuit controlling the AIR’s in less than 20 seconds.
[3, p. 16]

3.2 High Voltage System Protection and Distribution Unit

The inverters are positioned inside the HVSPADU. The function of the inverter is to convert the DC voltage distributed from the battery into Alternating Current (*AC*) for the three phase motors. The high level control comes from the VCU via the CAN bus.

The car is powered by two electric motors, each propelling a separate drive shaft to the rear wheels. Both motors are controlled separately with the objective of being able to set a specific shaft torque depending on the driving situation.

Figure 6. Motor controllers are positioned above the accumulator

3.2.1 Pre-charge and discharge circuits

Due to the fact that the pre-charge circuitry is implemented in the inverter itself, no separate circuit is added to the high voltage path for charging the capacitance in the inverters. Twelve capacitors are positioned in the inverters, which are charged through pre-charging resistors. The circuitry is controlled by the inverter's own system. The input voltage is set to charge the capacitors to 90 % of the DC voltage before opening the pre-charge circuit relays.

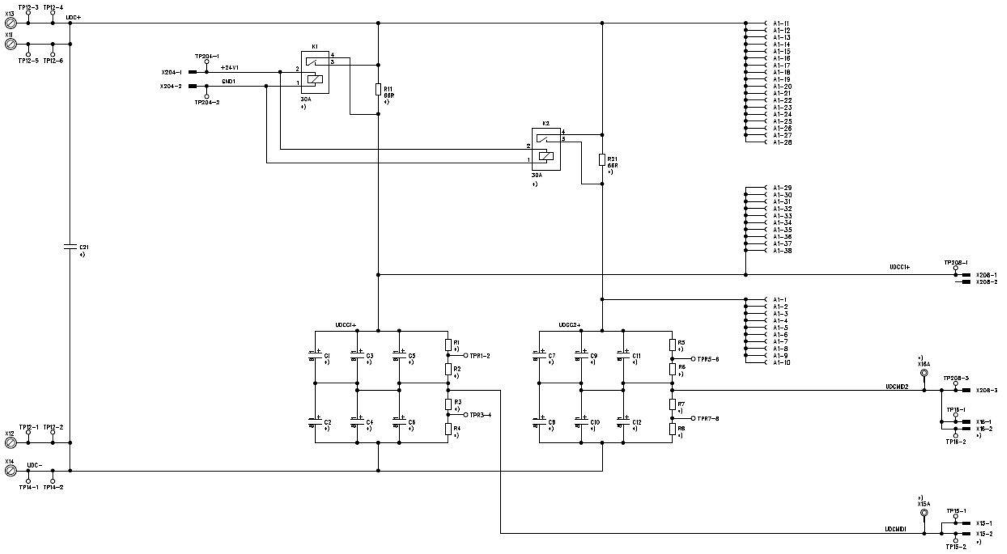

Figure 7. Pre-charge circuitry in inverters

The inverter also includes a discharge circuit. The discharge time, however, is quite long which is not rule compliant neither safe when disassembling the high voltage cabling for charging in a hasty situation. Two additional power resistors have been added to drain the energy from the capacitors in less than 5 seconds. This high power requirement is set by the FS rules.

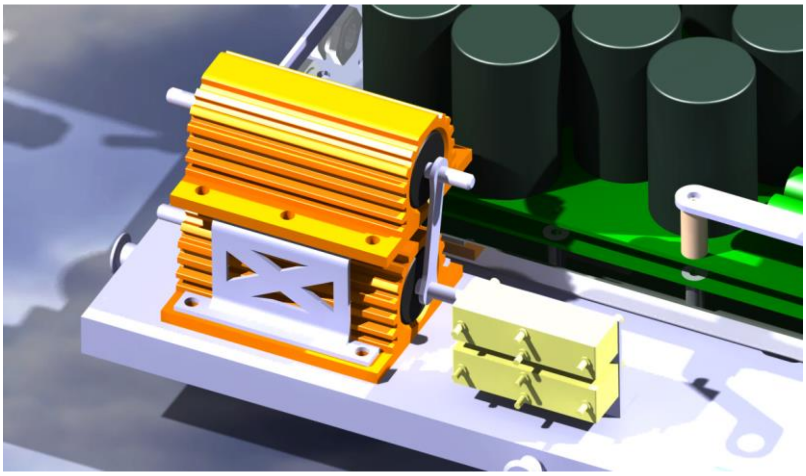

Figure 8. Discharge resistors and high voltage relays

3.2.2 Motors used in HPF015

Two servomotors are used in HPF015. The motors are of the same type and are Permanent Magnet Synchronous Motors (*PMSM*) type motors used originally in industrial applications. They have a power potential of 44 kW of axle power. The motor rotor and stator are made by Siemens AG, the motor housing and the reduction gear has been designed by Metropolia Motorsport. The motors use resolvers for precise feedback of the motor position.
[3, p. 52-53]

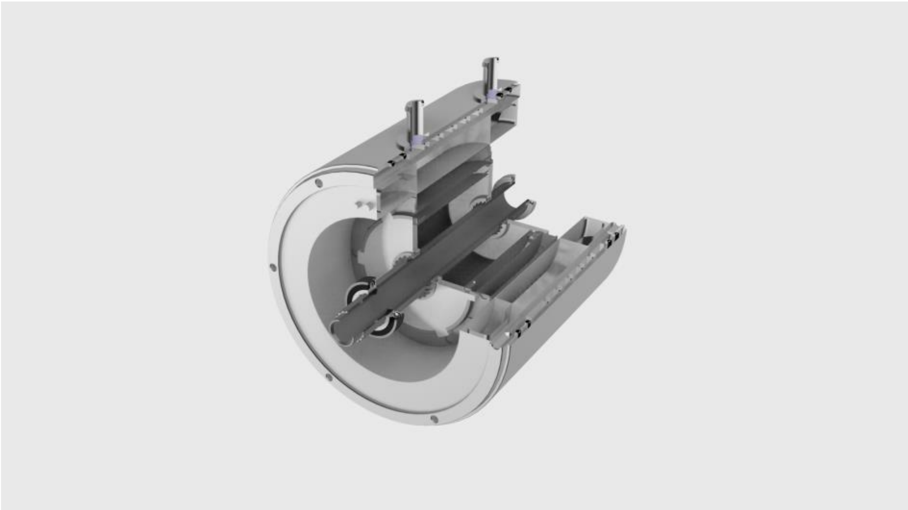

Figure 9. Powertrain caption

3.3 Existing control system

The control system in HPF015 is divided into three separate systems. The most important is the active system which holds the main CS. This contains the dash switches, torque pedal position sensor data, brake pressure data, acceleration data etc. The second system is for data logging purposes. This includes sensors such as suspension position, temperatures etc. The third ensemble is for settings and parametrising the AMS. All electrical systems rely on CAN bus for communication. The low voltage is distributed between the devices by a MoTec Power Distribution Unit (*PDM*).

The CAN modules are:

- *Inverter CAN module, left*
- *Inverter CAN module, right*
- *Accumulator Management System*
- *ElektroBit (VCU)*
- *MoTec ADL (Data logging)*
- *MoTec PDM*

The electrical system is tied together by using a wiring harness designed for harsh environments. Sensors and other necessary components as shutdown switches are also connected to the harness.

4 Design of New Control System

This chapter will introduce the most essential design phases of the CS. The different states of progression will be uncovered exactly as during the design work. Here the different systems will also be segregated for clarifying the functions of each one separately. Some of the terminology refers to the FS rules and will be explained while untangling the design process.

The design started from evaluating the system requisites. The Ground Low Voltage (*GLV*) system, HV system, Tractive System (*TS*) and CS had to be specified for a clear identification of each system.

The HV system is referred to as a system where the operational voltage is greater than 60 VDC or 25 VAC. Components such as high voltage wiring and TS housing are considered as a part of the HV system. The TS is referred to as every part that is electrically connected to the motors and tractive system accumulators.
[5, p. 99-100]

The GLV system is referred to as a system where the operational voltage is equal or below 60 VDC or 25 VAC. The GLV system of the car is defined as every electrical part that is not a part of the tractive system. The CS is referred to as the part of the GLV system that executes the functions of the GLV system.
[5, p. 99-100]

This clarification is done for the reader to understand that the CS system can control the TS within HV housing. This is critical information when declaring the HVSPADU and accumulator unit functions. In some cases the term “electrical system” will be referred to while explaining some behaviour of the car that is caused by either the TS or the CS.

4.1 System requirements

The electrical system requires a set amount of analogue and digital inputs/outputs (I/Os) to take care of the of basic functions, such as setting the car from an inactive state to a state where it can be driven. Considering the driver’s safety all GLV systems must have a galvanic separation from the HV system. Due to interference issues in the previous car, a better electromagnetic field protection has to be added and modified for assuring the functionality of the powertrain. The protection also has an objective to minimize the effect the TS has on the CS.

4.1.1 Ground Low Voltage System

Metropolia Motorsport builds one racer each year. Due to this fact some of the components are stripped from the old car for either spare parts or for fulfilling either a mechanical or an electrical system. The CS design started from a point with no main units for supplying power or controlling the cars electrical system. However, components from the accumulator and inverters were not dismounted.

All control units but the AMS and the CAN modules of the inverters were stripped from the car. This led to a need to replace the CS units. Due to a different mechanical layout the electrical components needed a new wiring harness. The other electrical system parts on the car as dashboard were rebuilt lightly for ease of use. The system design was only restricted by the capability of resource acquisition, technological knowledge and time.

The GLV system requires a low voltage feed for keeping it active while driving. With a 50 % power output this value is around 0. 7 hours in best case scenario. At this point the TS battery is drained to its limit.

The car possesses a set amount of data inputs for doing a start-up sequence. This is to ensure the car from having unexpected behaviour before the driver is ready to start. The system has to be able to send all gathered data via a data bus to a unit that can do calculations based on the inputs to result in a movement of the car. Finally, all components need a galvanic separation to ensure that the TS voltage cannot be present to the driver. These are the basic functions referred to in the objectives. The I/Os are shown below.

Components:

- *Torque sensors data for accelerating*
- *Brake pressure sensors data for start-up sequence and brake light*
- *Five switches including CS activation/shutdown, TS activation/shutdown and Ready To Drive Mode (RTDM)*
- *Ready To Drive Sound (RTDS), for warning spectators of the car being active*
- *Light Emitting Diodes (LED) for showing the states of the car*
- *Tractive System Active Light (TSAL)*
- *Option to restrict torque and speed by a potentiometer*
- *Fault marker*

Functions:

- *Read in/control the parts mentioned in the previous list of components*
- *Have a functional data bus for data exchange between units using ProfiNet*
- *Have both CAN buses functional for data exchange between the CPU and AMS*
- *Have all mentioned data (check components list) present in a data bus*
- *Use all mentioned data from components to activate the car and driving safely*
- *Utilizing data from TS for controlling it in a safe manner*
- *Readiness to log any data from TS*

4.1.2 High voltage safety

Most of the high voltage safety functions are provided by the previous system. All functions considering the accumulator e.g. insulation resistance measurement and cell monitoring are still active. The AMS will function in a manner described in the introduction of the accumulator management (*Chapter 3.1.3 Accumulator Management System*). However, the data provided by the AMS will be utilized by the VCU for functions described below:

- *Zero the torque request in a fault situation, this is done to keep the AIRs intact*
- *Restricting the power output based on the load of the batteries*

The inverter safety functions are similar to the old system and are not specifically described here, since they agree with the introduction of HVSPADU (*Chapter 3.2 High Voltage System Protection And Distribution Unit*).

4.1.3 Data logging

Data is logged from various systems of the car. It utilizes many analogue sensors, CAN data from the AMS, data sent from the inverters and data from the CPU slave units. The most important matter is to be able to log all data on the same time axis for a proper analysis. The quantity of necessary data memory of data varies from 4, 3 MB … 200 MB, and depends on logging frequency and time.

Since the earlier data logging has been incomplete, the necessary resolution and logging frequency was hard to determine. A minimum 42 MB was calculated for a proper sampling and higher values will be considered an advantage. The values are reasoned later in the thesis (*Chapter 4.2.2 Calculations*).

4.2 System design

The system design started with the intention to find or self-manufacture a module which could supersede the earlier used ElektroBit VCU unit. The power distribution and data logging were to be designed around the main unit depending on its features.
The brainstorming for the thesis started in November 2015, with a deadline to do the first test drives in late March 2016. The development schedule of the system would be approximately five months. Due to the schedule a self-developed system was not considered possible. It was discovered that the only available option was factory-made units which would only need to be implemented to the system.

During the autumn the results of the season and development were reported to sponsors. The inverters which were sponsored by ABB had been working reliably in most occasions. During the oral presentation the representative of the company mentioned about a possibility to implement their PLC technology to the car. The idea was taken into consideration, and due to sparse realistic options it was decided to dig deeper into the PLC unit possibilities.

After discussing with engineers and sales representatives, a suitable system series was found. The PLC series is called AC 500 – XC. Following a couple weeks of browsing brochures and datasheets of the PLC unit versions and I/O modules, appropriate units were found to fit the given requirements. The layout of the industrial components was convenient since its huge expansion possibilities. The final I/O layout can be found in Appendix 4.

4.2.1 Low Voltage battery calculations

Some design decisions required additional calculations to be made. These are the energy consumption of the GLV system and data logging memory.

Energy consumption was determined by listing all high consumers in the system and averaging a decent value for sensors and switches. Since the cooling fan and water pump are the highest consumers their power will be adjusted. This is taken to account by utilization rate in Appendix 5. The estimation, however, is slightly oversized to increase the GLV battery life.

A detailed list of components can be found in Appendix 5. The energy consumption is based on this calculation. This calculation is done only to prove the system functionality with maximum power for the whole load time. Due to spare battery cells from the competing season the same cells are used for GLV battery as for TS battery.
[6, p. 2]

The working voltage for the PLC is 24 VDC, and therefore the GLV system voltage will be increased from the old 12 VDC system to 24 VDC. Some minor changes were made to the old system to fit it with the 24 VDC system.

The power consumption calculation is done as following:

Estimated maximum power consumption:	*P = 379, 37 W*
The energy is then converted to Joules:	*3600 * 379, 37 W = 1 365 732 J*

The cell amount can be calculated based on this formula

$$\left(\frac{Mmax}{Mmax * 0{,}85} * Mmax * 0,7\right)/Mcell = Cq$$

M_{max} (J) = Maximum amount energy used in one hour
M_{cell} (J) = Energy of cell
0, 85 = factor for usable capacity
*0, 7 = factor for time driven (0, 7 * 60 min = 42 min)*

$$\left(\frac{1\ 365\ 732}{1\ 365\ 732 * 0{,}85} * 1\ 365\ 732 * 0,7\right)/85\ 248 = 13,19\ pcs$$

Based on the energy calculation the minimum of 13, 19 cells and the working voltage the cell amount is rounded up to 14, 00.

The nominal cell voltage is 3, 7 VDC, the usable voltage range is 3, 6 VDC…4, 1 VDC. By connecting seven (7) cells in series the working voltage will settle between of 25, 2 VDC… 28, 7 VDC.
[6, p. 2]

The cell energy is calculated as follows:

$$3,7\ VDC * 6,4\ Ah * 3600 = 85\ 248\ J$$

The energy will allow to drive the car for a minimum of:

$$85\ 248\ J * 14 * 0{,}85 = 1\ 014\ 451\ J$$

$$\frac{1\ 014\ 451\ J}{1\ 365\ 732\ J} * 100\ \% \approx\ \ 74\ \%$$

$$0{,}87 * 60\ min = 44\ minutes$$

4.2.2 Data logging calculations

During the earlier seasons the data logging system had issues due to low memory. The maximum logging memory was only 8 MB. The argumentation for adding more memory capacity is shown below:

The data to be logged is calculated based on the amount of input data chosen to be logged by the system supervisor. The logging frequency used is the average frequency for all signals. When all signal samples for one second are added together the following calculation can be done. The detailed calculations for different logging times and sample rates can be found in Appendix 2. Note that this calculation does not take into account the amount of memory required by the software to save the data.

The calculation is demonstrated below:

The logging session will be twenty minutes long. This equals 1200 seconds.

Logging time = 1200 seconds
Sample rate (avg) = 18 069 Hz

$$1200\ s * 18\ 069 \frac{S}{s} = 21\ 682\ 800\ S$$

The sample amount is then 21 682 800 S. Every sample will need a 16 bit memory, which equals two Bytes.

Samples = 21 682 800 S
Bytes/S = 2

$$21\,682\,800\ * 2\,Byte = 43\,365\,600\,Byte$$

$$\frac{43\,365\,600\,Byte}{1024\,000} = 42,34\,MB$$

The required memory for a good data logging session contains driving for a minimum of twenty minutes, the needed memory is then 42, 34 MB. This quantity of data would give the system supervisor a good understanding of the behaviour of HPF15 during a half session and is therefore considered the minimum value required for the data logging memory.

4.3 Communication bus

It has already been shown that when utilizing the full system, a large amount of data has to be relocated into the CPU, and this is done either for data logging purposes or to exploit the data altering dynamic behaviour of the car.

The HPF015 AMS utilizes CAN 2.0 communication protocol, which is a specification for automotive use. The CAN bus protocol used in industrial applications is known as CAN-open. To use the PM592 CPU with the existing AMS, two separate CANopen master units were fitted to the terminal base with the PM592. The first CAN bus is employed for parametrising the AMS, and the second to exploit the data for dynamic control of the battery.

The second connection had to be made between the PM592, the inverters and the I/O slave unit in the front part of the car. This connection had earlier been via CAN bus but was replaced due to an interest of testing an Ethernet based data bus. Since an industrial PLC was used, the variety of different data buses was significant.

There are several different types of Ethernet based protocols for industrial applications. A suggestion from ABB came for using ProfiNet, which is a very widely used industrial Ethernet. The choice was made quite easily since ProfiNet outperforms CANopen in all dynamic aspects. This will be clarified in Chapter 4.3.1 and 4.3.2. The usage is also large, which leads to a remarkable number of suitable I/O modules. The final decision was made based on the data bus prevalence.

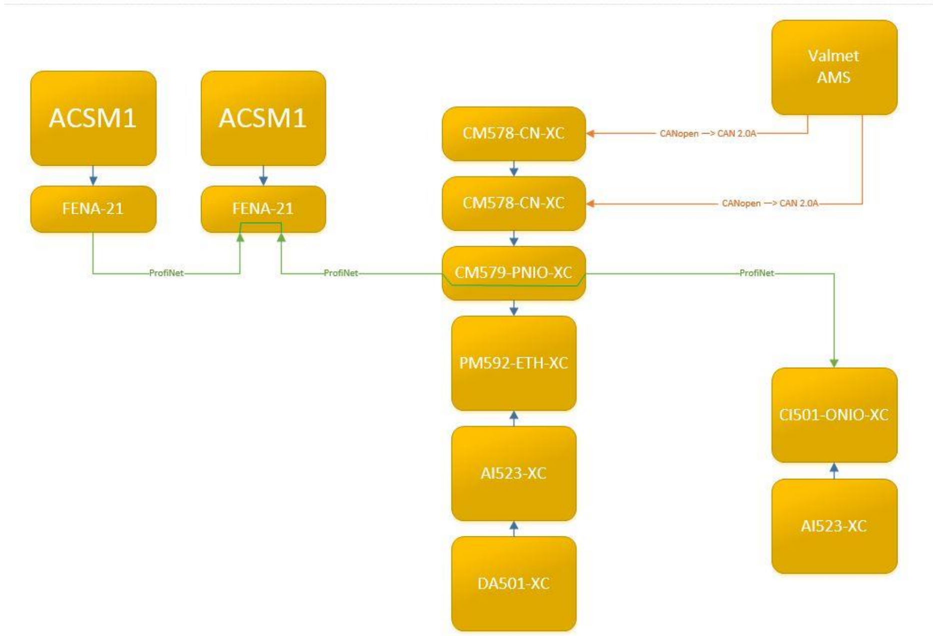

Figure. 10 Data bus layout

4.3.1 CAN bus introduction

The CAN bus is a serial multi master communications protocol developed by Bosch GmbH. It supports distributed real-time control and possesses a maximum signalling rate of 1 Mbit/s. the functional principle is based on sending data in small packages to the bus which can then be collected by devices it is directed to. The intention of the protocol is to achieve a compatibility between devices made by different manufacturers.
[7, p. 6]

The CAN has been divided into different layers to achieve implementation flexibility.

- *The (CAN-) object layer*
- *The (CAN-) transfer layer*
- *The physical layer*

The object layer specifies how messages are filtered. This includes finding messages that are to be transmitted, deciding which data on the bus is used in the application and providing an interface to the application layer related hardware.
[7, p. 6-7]

The transfer layer represents the kernel of the CAN protocol. The fault confinement, error detection and signalling and message validation are found here. Additionally acknowledgements, arbitration and message framing are included. As last the transfer rate and timing is set by the transfer layer.
[7, p. 7]

The physical layer defines the actual transmission of signal. This includes bit representation and signal level as well as transmission medium which can be optimized for its application.
[7, p. 8]

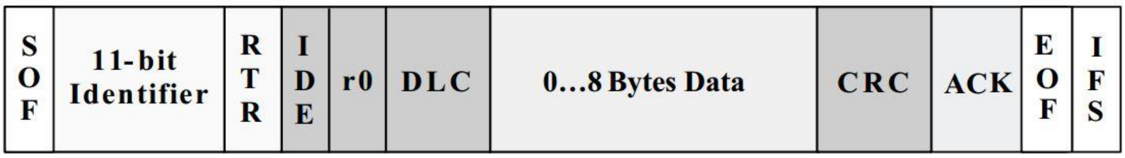

Figure 11. The physical layer of CAN

The CAN bus bit stuffing can be seen in figure 11. The meaning of the bit fields are:

- *SOF – The single dominant start of frame (SOF) marks the start of a message. It is used to synchronize nodes on a bus after being idle.*
- *Identifier – The standard CAN 11 bit identifier establishes te priority of the message.*
- *RTR – The single remote transmission request (RTR) bit is dominant when information is required from another node.*
- *IDE – A dominant single identifier extension (IDE) bit state a non-extended data identifier is being transmitted.*
- *r0 – Reserved bit (for future use)*
- *DLC – A 4 –bit data length code (DLC) contains the number of bytes being transmitted*
- *Data-up – 64 bits of application data.*
- *CRC – Cyclic redundancy check (CRC), 15 bits plus delimiter contains the checksum of the preceding application data for error detection*
- *ACK – Every node receiving an accurate message overwrites this recessive bit in the original message with a dominate bit, indicating that an error free message has been sent.*
- *EOF – End of frame (EOF) is a 7 – bit field that marks the end of a CAN frame and disables bit stuffing, indicating a stuffing error when dominant.*
- *IFS – A 7 – bit interframe space (IFS) contains the time required by the controller to move a correctly received frame to its proper position in a message buffer area.*

[7, p. 12]

In automotive use, the CAN bus is used for networking the car and to reduce the use of wiring. However, the CAN bus is a non-deterministic data bus, this conducts to some issues when a real time system is to be made. Firstly, the non-deterministic behaviour designates that communication delay is not predictable. Secondly, it cannot withstand a load much higher than 30 %. This leads to a restriction in the amount of data being sent. Lastly and most importantly, the transfer rate of a CAN system is typically between 1 Hz… 100 Hz. This might cause restrictions in real time systems.

In data logging purposes, some of the data might be logged at as high as 200 Hz… 1000 Hz rates. If the data is logged through CAN, the actual transfer rate might undercut the logging frequency needed. Even if the system is logging on high frequency it might log the exact same value buffered by the CAN device.

The industrial CPU uses a CANopen protocol. CANopen comprises higher layer protocols and profile specifications. In practical sense it can be understood as a CAN system, which includes addressing data in the identification address that positions it e.g. in a temperature output. The protocols might include remote or event based data requests as well. These protocols allow industrial functions to be standardized more easily.

In HPF015 the AMS sends data with CAN 2.0 A protocol and therefore specific requests for accumulator data will not be done. Instead the data from the AMS will be sent at regular intervals. Since the system comprises of only one CANopen device that communicates with one CAN 2.0 A device, no higher level protocols are needed. In practical sense this means that only single CAN messages will be created in Automation Builder 1.2 (focused on in Chapter 7).

4.3.2 ProfiNet introduction

ProfiNet is based on the Ethernet 802.3 standard given by Institute of Electrical and Electronics Engineers (*IEEE*). One of the significant properties of the Ethernet is its simple structure. Due to this fact it has been implemented largely. ProfiNet is the open standard for the industrial automation based on industrial Ethernet. The ProfiNet technology was developed by ProfiBus Nutzerorganisation e.V (*PNO*) and utilizes relevant Transmission Control Protocol (*TCP*) / Internet Protocol (*IP*) for setup, configuration and maintenance functions.
[7, p. 3]

ProfiNet is separated into two function classes, the ProfiNet IO and the ProfiNet CBA. ProfiNet CBA is a concept designed for distributed industrial automation applications. It is intended for controlling larger systems and can work as a backbone network. This work does not utilize it and it is therefore not dressed in this theory section.
[8, p. 1]
ProfiNet IO uses three different communication channels. The standard TCP/IP channel is used for parametrisation, configuration and acyclic read/write operations. The Real

Time (*RT*) channel is used for standard cyclic data transfer and alarms. The third channel Isochronous Real Time (*IRT*) is the high speed channel used for Motion Control applications.
[7, p. 15]

To better understand the ProfiNet communication it can be divided into segments. These segments make up the so called International Standardization Organization (*ISO*) / Open System interconnection (*OSI*) reference model. The model divides the communication operation into seven layers, where each layer comprehends its own specified assignment. In figure 12 a visual representation of the layer can be seen.
[10, p. 5-6]

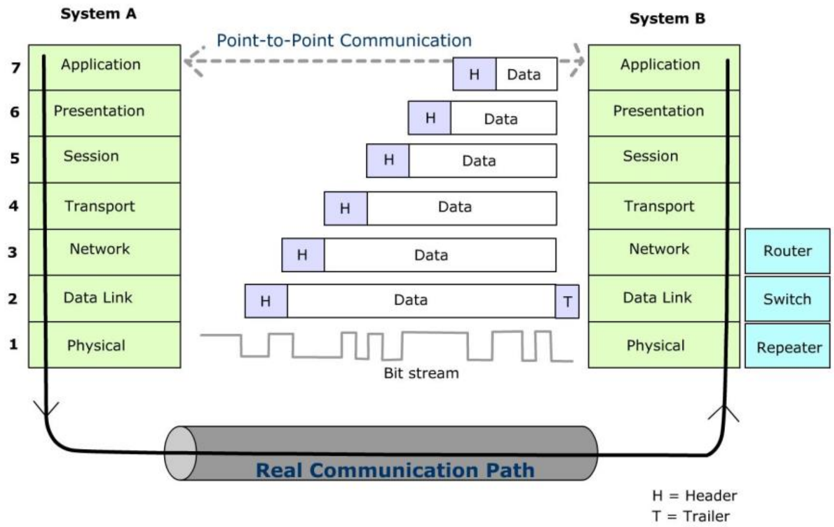

Figure 12. ISO/OSI reference model

Layer 1: Physical layer

The physical layer is where the single bits of the data are physically transmitted. This layer incorporates the electrical and mechanical properties of the bus. This includes voltage levels on the bus, cable types, pin assignments etc. ProfiNet functions on this layer by fast Ethernet with 10… 100 Mbit/s according to the standard from IEEE 802.3. The data transmission is bidirectional.
[10, p. 5-6]

Layer 2: Data link layer

The data link layer delivers error free data transmission between two users to the layer three. The data is split into frames, which enables the data to be checked by the receiver. In case of a faulty data frame, the respective frame is requested again. This layer also includes the Medium Access Control (*MAC*), which is given to the device by the manufacturer. The MAC address consists of the manufacturer identifier and the consecutive numbering. The PNO offers the device manufacturers the manufacturer identifier part of the MAC address. This part is also known as Organizationally Unique Identifier (*OUI*).
[10, p. 5-6]

Layer 3: Network layer

The network layer enables communication between users and between network types. Data packets are transmitted by using their IP addresses. The suitable routing will be selected here. The packets will be temporarily saved on the subnodes and they will look at the current routing table, finding the most suitable route and then forward the packets along the route respectively. When using the ProfiNet on an object, an engineering tool is to be used for setting the IP address. The ProfiNet device can be accessed by using an appropriate tool for the system. Its purpose is to find the IP address of the device.
[10, p. 5-6]

Layer 4: Transport layer

The transport layer has the assignment of ensuring the communication connection. The data packets will be fragmented by the transmitter and defragmented by the on receiver. In a case of error in the data caused by e.g. lost or erroneous data the errors will be corrected. The error correction will be made by using for example receipts or repeated requests. In time critical applications the User Datagram Protocol (*UDP*) will be used to control data flow.
[10, p. 5-6]

Layer 5: Session layer

In this layer the services like a dialog control for the supervision of data flow or recovery points will be actualized. If a connection is interrupted, it can be recovered at the last point. This layer, however, is not used by ProfiNet.
[10, p. 5-6]

Layer 6: Presentation layer

This layer will be translated into the common format on this layer. The data will be coded and compressed by the transmitter. Decoding and decompressing is correspondingly done by the receiver. The final part is to send the data to the respective application. This layer, however, is not used by ProfiNet.
[10, p. 5-6]

Layer 7: Application layer

The specific interface used in the application will be defined on this layer. These interfaces enable the communication between applications. The communications between different protocols will be implemented by using so called gateways or proxies. This type of control between applications might be necessary when a desire of uniting different field buses into the system is wanted.
[10, p. 5-6]

4.4 Wiring harness design

The wiring harness is the main component for binding the electrical system of the car together. It links units, sensors and switches together and acts as a nervous system of the car. Since HPF015 is an open wheel type formula car, the wiring harness will encounter harsh environments and the post season testing might take place on non-standard events including testing on ice tracks.

Durability and maintenance were the main criteria for the design. Due to the unusual needs of the wiring harness, no specific standard of design or manufacturing was used during its design. Additionally the high price of standards given out by SAE was considered as an unnecessary cost.

The design was intended to be created using a Computer Aided Design (*CAD*) software. However, the installation of the necessary software was not made at the university due to issues with the distributor. The system design was finally created in a Matlab subprogram known as Simulink alongside with the schematic. The first versions were drawn by hand to brainstorm an adequate layout. The technical drawings are then incorporated to a pdf file for preceding reviews.

4.4.1 Wiring harness layout

The electrical system consists of the CPU with its slave units, the accumulator and inverter and a significant number of small components mainly consisting of sensors and switches. HPF015 utilizes only a few signals for its basic functions (see Chapter 4.1.1). The rest of the system is for data logging purposes and system extensions. Due to this fact the harness was divided into segments which from each part meet with a specific part of the car. A few parts of the main harness were made into so called active system parts and some for data logging.

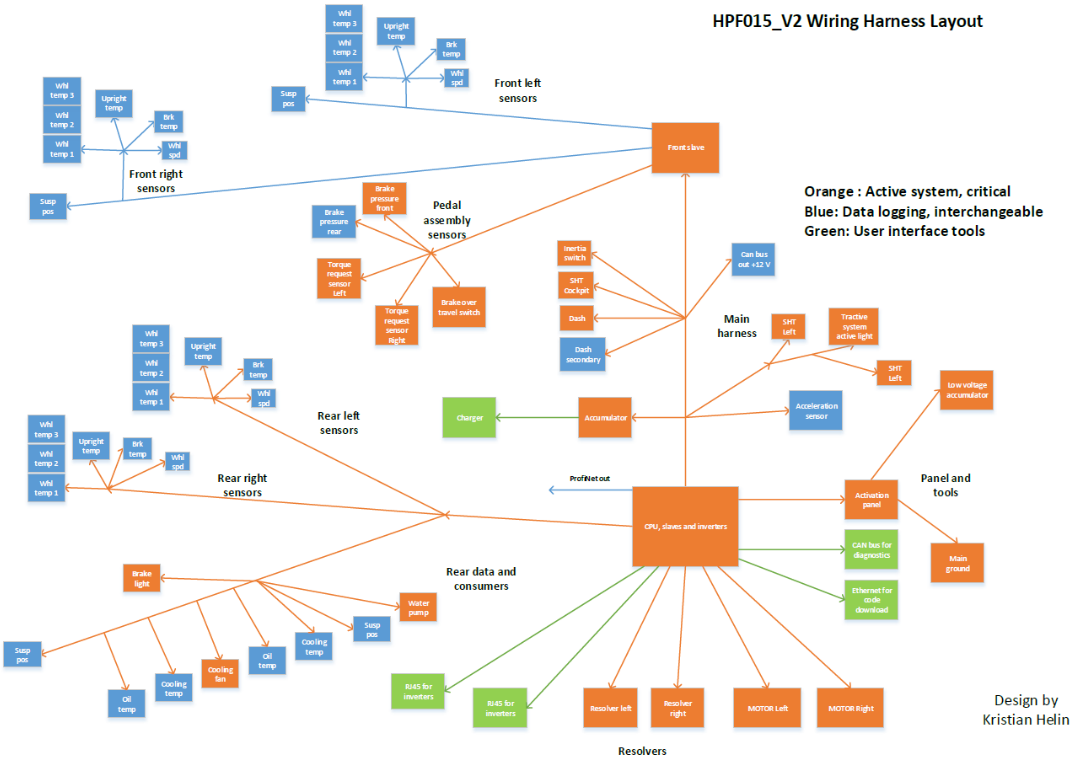

Figure 13. Wiring harness layout in Windows Visio

In addition to the objectives of the thesis, an option to add different sensors to the car or partly remake the harness for testing had to be considered. Therefore, the harness was divided into eight separate pieces (with the HV cabling excluded) for the active system and additionally two interchangeable wiring harness parts. This permits adding or changing sensors to the system if necessary by only remanufacturing a small piece of the wiring harness. The main housing of the systems was also equipped with a bushing including an adapter for further extension of the ProfiNet. The technical drawing can be found with high resolution in Appendix 3.

4.4.2 Wiring diagram

The wiring diagram for the car was made after choosing the final PLC components. However, it was considered convenient to introduce it to the reader at this phase for clarification of the position of each unit.

Firstly, the data bus layout was made as a base to start designing the wiring harness and the circuitry around the I/O units. Some parts of the old 12 VDC system had to comply with the new 24 VDC system. This implementation only took place for the water pump, brake light and cooling fan. The components were fitted by using 12 VDC regulators for supplying power, the power was then fed to the devices by controlling MOSFETs with digital outputs of the DA501 unit. The sensors were supplied from 24 V → 5 V converters. In addition, few components were needed. A higher detailed picture of the wiring harness can be found in Appendix 6.

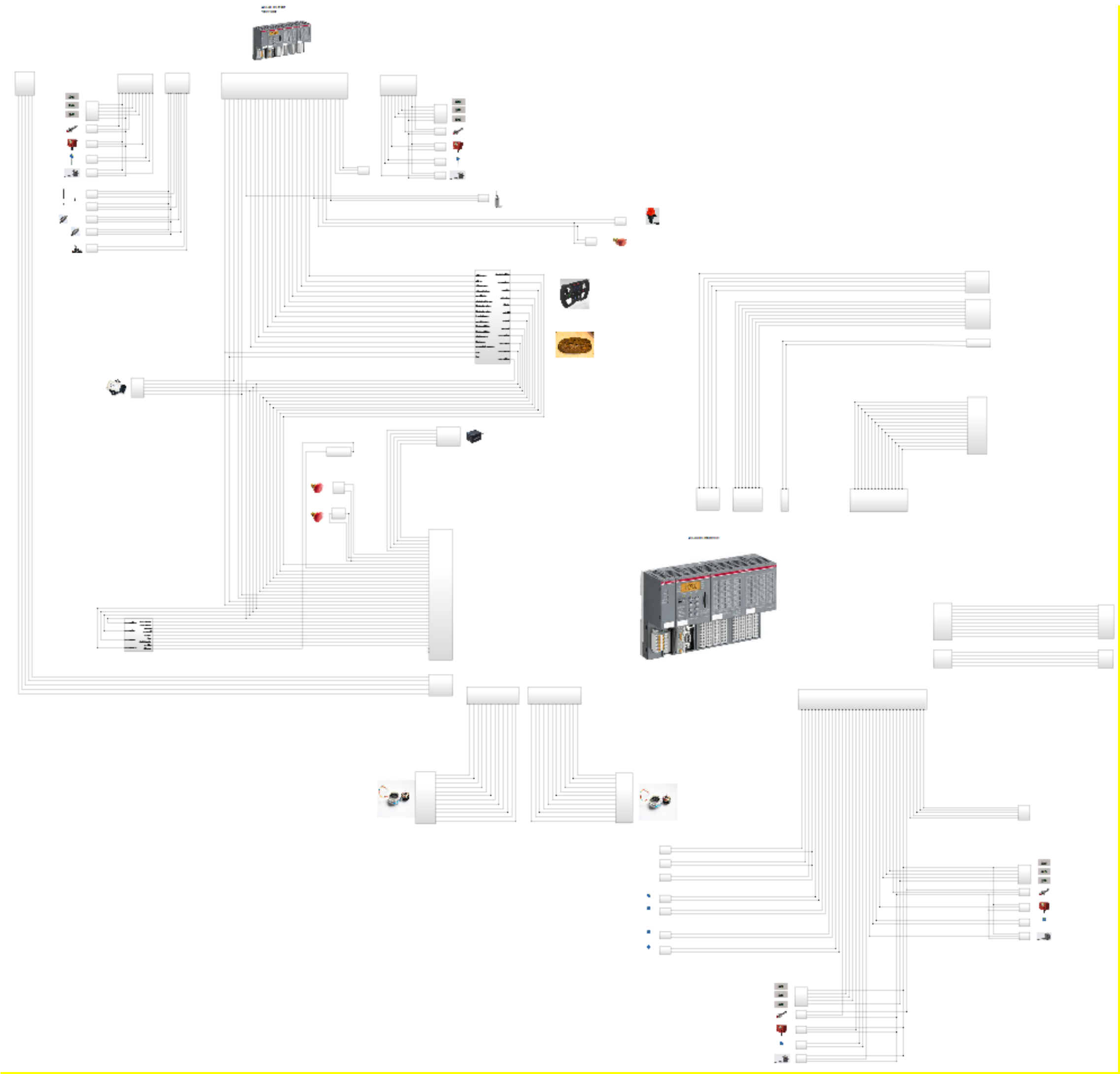

Figure 14. Wiring harness schematic

5 Final component choices and exploring of features

The final choice of components for this project was based on four criteria: affordability, implementation possibilities, code development time and the number of necessary modifications needed for the original system. Due to the schedule, it was decided to stay within the already existing units. Since the inverters of the car were manufactured by ABB which had been a prior sponsor for the car, it was only natural to use their PLC components.

Finally, ABB was the only realistic component manufacturer which could supply the parts within the given timeframe as a sponsorship. Since ABB seemed interested in supporting the project, discussions were held to choose the best fitting components for the project.

5.1 ABB AC500 XC series

AC500 –series was considered as the most suitable series. The marking XC refers to eXtreme Conditions. It is used in harsh industrial environments where everything from humidity to salt, vibrations and different temperatures might take place. In general it is a subseries from AC500 and is available with similar features. The car will operate in environments such as rain, water spray tests, high accelerations and vibrations and the system will therefore need this type of protection.
[10, p. 86-117]

Figure 14. AC500 with two communication modules and two I/O modules

5.1.1 Central Processing Unit (CPU)

PM592-ETH-XC is the Central Processing Unit (CPU). The choice from different options within the series was done based on its data logging capability, which is up to 4 GB. The device is accountable for both the VCU tasks and data logging in the car and is considered as the VCU. With a program memory of 4096 kB and high in data logging memory it exceeds all requirements. For diagnosis and status functions, a simple display and eight function keys are integrated by the manufacturer.
[10, p. 55]

PM592-ETH-XC is expandable up to 10 I/O modules for a total of 320 digital I/O's or 160 analog I/Os. Expansion modules can be connected to either the CAN bus or ProfiNet with separate units. Due to space issues in the car an expansion using the terminal base is not possible. However, the ProfiNet or CAN can be used for expanding the system.
[10, p. 56, 61]

5.1.2 Communications modules

The backbone network for HPF015 is ProfiNet. CM579-PNIO-XC is a communication module for connecting the PLC to slave units in the communication bus. The communication module is equipped with two RJ45 connectors for connecting to the physical data bus. It is capable of controlling the ProfiNet with a speed up to 100 Mbit / s. To connect the inverters to the ProfiNet, FENA-21 modules were installed. They work as ProfiNet slaves and operate the communication between the CPU and inverters.

The AMS uses two separate CAN 2.0 A buses which work as secondary data buses in the car. The buses are connected to the CPU with two CM578-CN-XC units.

In the front part of the car a CI501-PNIO-XC unit is positioned. It is a combined ProfiNet communication and I/O module. It uses a separate terminal base and is connected to the CPU only via ProfiNet cable. This is considered as the front slave communication unit. It is equipped with four analogue inputs, two analogue outputs, eight digital inputs and eight digital outputs.

5.1.3 I/O units

AI523-XC unit can be found in both the front and the rear of the car. It is solely for expanding the communication unit with analogue inputs. AI523-XC simply connects sixteen analogue inputs to the CPU via the communication unit (*CI501-PNIO-XC*). The inputs are configurable e.g. to ±10 V, 0…20 mA or 4…40 mA inputs.

As the system requires a significant number of I/Os the DA501-XC unit was added to the system. It adds four analogue inputs, two analogue outputs, sixteen digital inputs and eight configurable digital outputs. Two of these digital inputs are configurable to high speed counters which are used for reading the wheel speed data.

6 Manufacturing and assembly

The design of the CS was intended to be finished during January. However, issues with finding a sponsor for wiring harness connectors delayed the project as the final pinouts could not be created. This caused a delay of the project for approximately five weeks. After the withdrawal of the sponsor, the university purchased the necessary parts, which allowed the project to continue.

6.1 Manufacturing of housing and mounting PLC components

The composition of the HVSPADU started in early January. Updating the system started with dissembling the old inverter housing and cleaning the aluminium cooling plate. The inverters were inspected for visible defects. The inverters were then reassembled onto the cooling plate. The old FCAN-01 expansion cards, however, were replaced with the new FENA-21 expansion cards to convert the CANopen communication to ProfiNet. Due to the position of the PLC, the HV conductors had to be replaced to fit inside the new housing.

The next phase was to design a new housing for the inverters that could fit the new PLC units. It was decided to place the PLC units at the side of the inverter where the energy meter and discharge circuit were earlier mounted. The PLC units barely fitted inside the new housing. Additionally, the discharge circuit was placed on top of the right inverter. The housing itself was manufactured of a material comprised of two pre-painted sheets of 0. 3 mm aluminium with a solid polyethylene core. The material was available at a local hardware store and was easy to work with.

Figure 15. Inverters assembled on the aluminum cooling plate

The second casing to be manufactured was for the front slave unit. The unit consist of only two PLC components and is very compact. The unit, however, it is not waterproof. A casing similar to the inverters was built around the front slave.

6.2 Electrical Installation

The electrical installation for the inverter was a quite straightforward phase. The inverter only needs a 24 VDC supply, a functional data bus, resolver wiring and HV conductors for critical functions. Additionally the discharge circuit and two fans were wired to support the critical functions. A large amount of the visible wiring consists of digital and analogue I/O channels wired to the connector on the side of the housing. The 12 VDC and 5 VDC converters were mounted inside the inverter housing. The wiring for the PLC units was done in the car since none of the connectors needed were at disposal.

High voltage wiring was installed separately from the CS, and three bushings were mounted into the housing for the high voltage wires. One bushing was made for DC voltage to supply the inverter, and two for feeding the motors power.

The inverters´ aluminium cooling plate is used as a main ground plane. The TS cable shields are robustly mounted to the inverter. This was done on the earlier installation; however, the grounding has not been made according to the manufacturer's directives. The final grounding is done in 360 degrees to minimize the transfer impedance in the connection. Additionally Protectional Earth (*PE*) wiring was added to the system.
[12, p. 67-69]

The front slave unit wiring was a very simple task. The unit only consists of analogue and digital I/Os, which were wired to waterproof connectors in the housing. Only additional 12 VDC and 5 VDC converters were added to supply the sensors.

6.3 Wiring harness manufacturing

The wiring harness manufacturing was to be started already in late January but was delayed due to a sponsor withdrawal. Since a sponsorship for the wiring harness connectors was expected, the system was already designed based on specific parts. Redesigning the wiring harness, requesting quotes and shipping of equivalent parts took five weeks, which shifted the project into a significant delay. Luckily, Helsinki Metropolia UAS decided to sponsor the necessary components and the project could continue as intended without an external sponsor.

The wiring harness connectors arrived on 14 March. Since no CAD models of the parts were made, the wiring was expiated onto the car's frame. The pinouts were determined based on the Simulink model. The wires were then laid into bundles and twisted to endure flexion. The wire bundles were protected using polyolefin heat-shrinkable tubing. The branches were additionally sealed with moulded heat-shrinkable shapes. The connectors were protected similarly for an optimum strain relief and a waterproof finish.

Figure 15. Wiring harness wiring is twisted mainly to create even strain when deflected

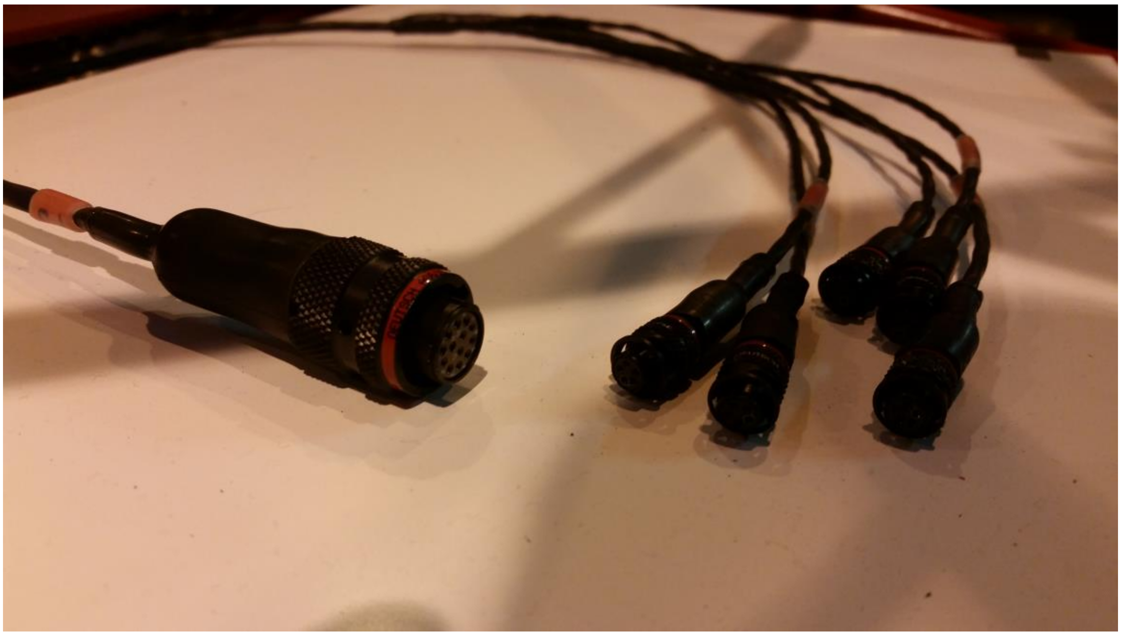

Figure 16. Moulded heat-shrinkable parts were used for optimum strain relief and waterproof finish

7 Automation Builder 1.2

ABB uses an integrated software suited for programming the AC500 CPUs. Automation Builder 1.2 is a software for configuring the AC500 hardware. In this environment the hardware can be handled. This includes diagnostics of the units, field bus communication node actions and data transmission, read in of raw data and other tools for ensuring the functionality of the hardware.

7.1 Controller Development System and IEC 61131-3 international industrial standard

Controller Development System (CODESYS) is a software platform designed for different requirements in industrial automation projects. It supports all five programming languages of the IEC 61131-3 international industrial standard, these are:

- *IL (Instruction list) is an assembler like programming language*
- *ST (Structured text) is similar to programming in PASCAL or C*
- *LD (Ladder diagram) enables the programmer to virtually combine relay contacts and coils*
- *FBD (Function block diagram) enables the user to rapidly program both Boolean and analogue expressions*
- *SFC (Sequential function chart) is convenient for programming sequential processes and flows*

CODESYS is used by multiple manufacturers as a platform to connect to their hardware. By using the platform, the variables used in the hardware can be guided to variable registers, which makes the coding process easier for the system engineer. Typically the hardware of the CODESYS compatible devices include the software license when purchased. This is one of the main reasons why CODESYS is becoming more common.

7.2 Setting up system to ready to drive

The first step when setting up the system was to set the IP address for the CPU. This is done to enable the configuration of the CPU. The setting was changed by using the network settings of the PC and sending a new configuration to the CPU according to the manufacturer's instructions. When the IP address was set, system components were brought to the "component tree" in Automation Builder 1.2. The "components tree" correspond with the hardware of the car.

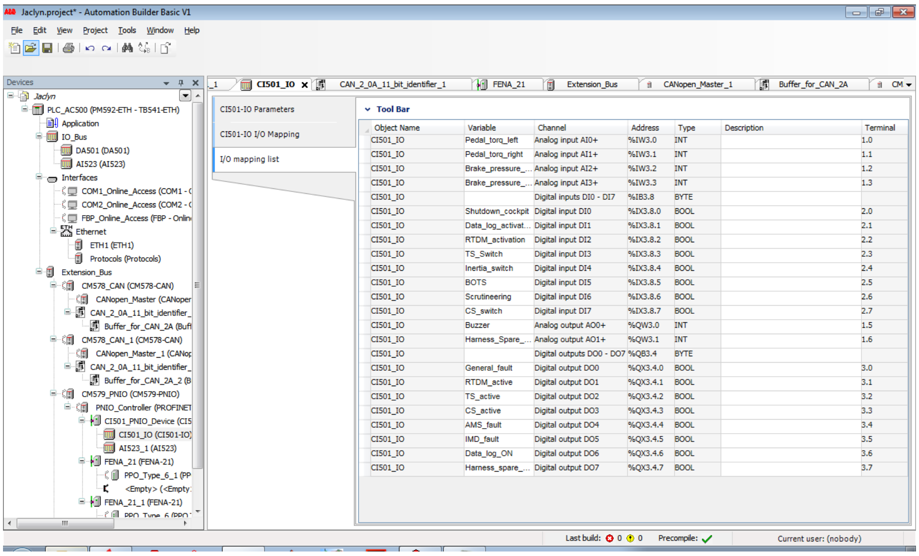

Figure 17. "Component tree" on the left side of the figure in Automation Builder 1.2

As seen on the right side of figure 18, the hardware I/O mapping was done in the software by simply writing the variable name into the given location. The inputs were parametrized in another tab. The parametrization included setting voltage levels and type of input. When an input is named, it is transferred to the global variables of CODESYS, which is the programming environment Automation Builder uses.

Followed by the setup of the I/O modules, ProfiNet was set into action. The ProfiNet was scanned to find the existing units with Automation Builder 1.2 engineering tool. Beneath the extension bus tab in the component tree (Figure 18) the CM597-PNIO-XC tab can be found, the view can be seen in Figure 19. After scanning for devices the IP for the units can be changed. After setting the IPs the front slave unit immediately starts to send data into the ProfiNet, however the ASCM1 inverter units had to be setup separately.

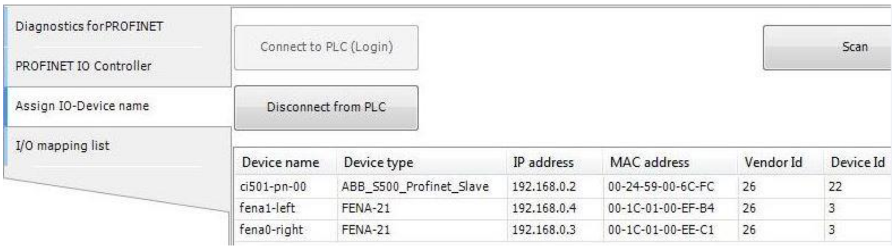

Figure 18. Scanning of ProfiNet devices

Each inverter uses a FENA-21 field bus adapter for transferring data into the ProfiNet bus. These devices have certain addresses known as PPOs, which need to be addressed with a specific data package from the inverters. This is done by the ACS-CP-U engineering tool.

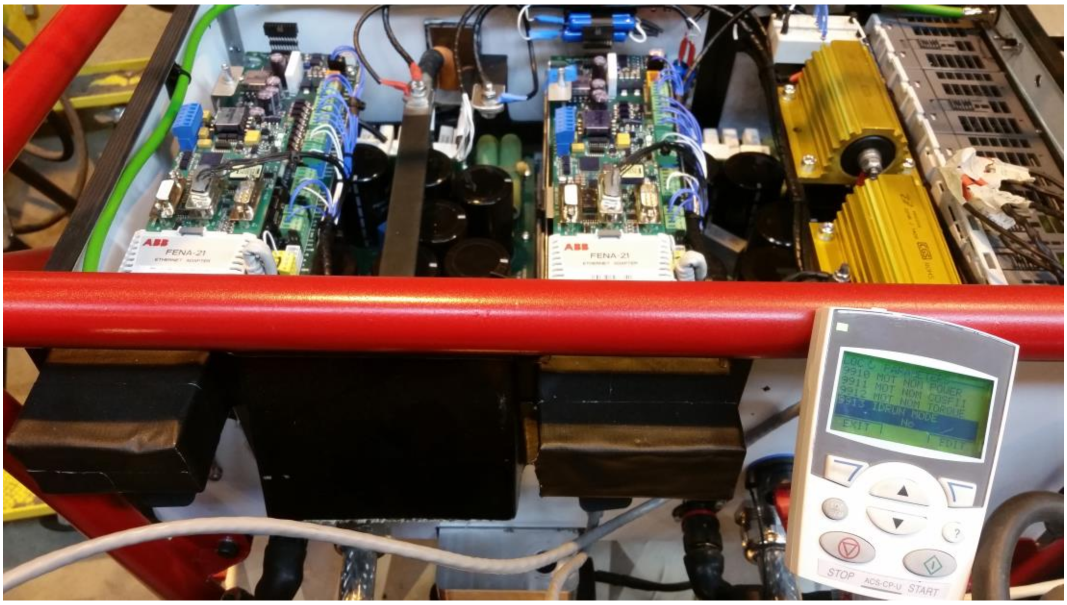

Figure 19. ACS-CP-U Engineering tool is used for setting up the drives.

The raw data read by the different slave units can be seen in the Automation Builder 1.2 to confirm that the signal source is connected correctly. The data in ProfiNet can be seen in figure 20, however, some messages show no value due to the motors are in a standstill state.

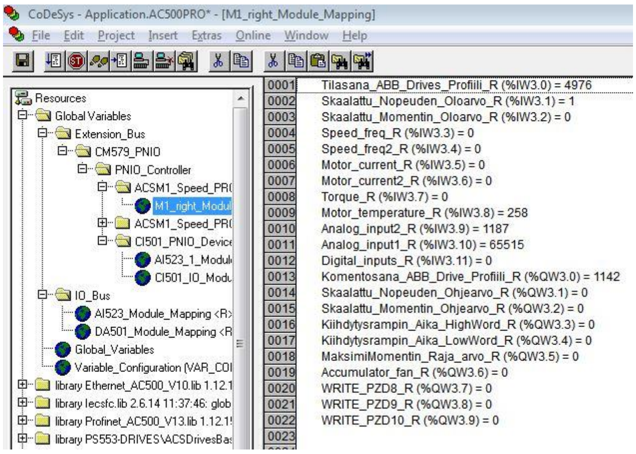

Figure 20 Pointers are set in the inverters to send the correct messages to the PLC

Before the motors were to be run by the PLC controller an ID RUN had to be made, to assure the correct motor parameters are used. After this the motors were setup for a high level control. At this point the inverters required state machine control and a torque request.

7.2.1 Safety functions

The first and most important point of the safety system is to monitor data from the AMS. Due to earlier issues with the system´s solidity, a higher level control of the AIRs control was considered necessary. Data sent by CAN from the AMS is utilized in the PLC to limit power output. Data as maximum and minimum cell voltages, pack voltage and temperature etc. are monitored, the system limits output torque when the load increases close to given limits. Since the CAN data is transmitted only every 150 ms from the AMS, the inverter DC link voltage data is used to support the safety of the battery limits. Due to the high performance of the PLC the torque output can be limited in less than 5 ms. this takes to account all data transmission delays and program cycle.

As the inverter is an industrial unit it has got very sophisticated safety functionalities of its own. Therefore, short circuit, overcurrent or sensor faults etc. can occur only for a very limited time. Due to this fact the system only needs higher level control to limit temperature limits to maximize dynamic performance. Data as inverter and motor temperature can be sent to the PLC via ProfiNet to limit torque in case temperature limits are approached.

Inputs such as shutdown buttons, inertia switch, Brake Over Travel Switch (*BOTS*) and IMD were read in to the PLC to support the safety of the vehicle. The states are used to determine if any of the shutdown systems are active. The state of the AMS is followed through the CAN bus. In case of an activation of the shutdown system the torque request is set to zero to release the load on the AIRs and open then after a 500 ms delay.

The start-up of the system is determined based on states of switches, the final RTDM state is activated by a press of a switch and activating the brake system. The different states of the car are shown to the driver with LEDs.

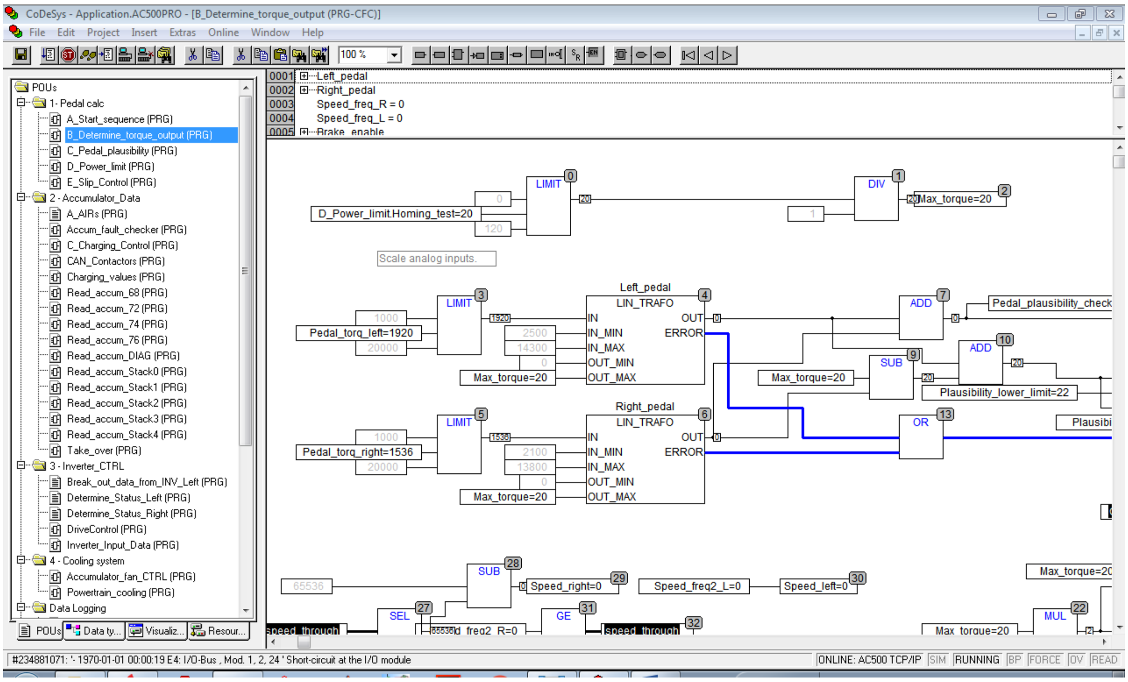

Figure 21. An example from the code where the acceleration pedal data is scaled.

7.2.2 Data logging

The data necessary to be acquired for analysis is gathered from three main systems, the accumulator, the inverters that include motor data and the dynamic system of the car. This is done to understand how the different systems operate with each other.

The PLC is capable of logging data in high amounts. However, ABB which manufactures the devices typically program these types of functions to customers. This leads to a lack of UI (*User Interface*) and the data logging functions have to be programmed by the user.

Due to the difficulty of programming, the data logging was limited to forty input signals. The data is stored on a SD card in the PLC wherefrom it can be loaded through a FTP (*File Transfer Protocol*) server. Since the flash memory is not used and the used code is still inefficient, it is limited to the program memory of the PLC which is 4 MB at the time. In practical use this signifies that for every data package the car needs to be stopped for approximately 30 seconds. This cycle can be continued until the mounted 128 MB SD card is full. Since the overall program memory requirement of the car is very low, the program memory can be utilized to a very high percentage.

In practical terms this means that 4MB with the data type WORD can gather approximately two million samples at the time. This ends up with a limitation of forty signals in WORD form at eight minutes when logging at 100 Hz. For endurance driving, logging can be used at 10 Hz to study the overall behaviour of the car and driver over a much longer period of time.

Since the data is loaded from the FTP server, any user with the login information can use the logged data from the car for further analysis. This is done e.g. with Filezilla.

7.2.3 Charging

Metropolia Motorsport uses two Brusa NLG5 chargers. Since the nominal voltage of the accumulator is 518 VDC, a single charger is not capable of charging the accumulator near to the maximum capacity. The chargers are connected in series to supply a high enough charge voltage for the accumulator.

The charge cycle has earlier been controlled by the internal software of the chargers, a control pin from the AMS and a charge state indication signal by a digital pin. Since the CS of every car varies slightly, it is difficult to fit the chargers to cars of different generations. Since no significant alteration in the FS rules have been done regarding charging in a few years, it was possible to make a control suitable for all accumulators in the future.

As the chargers are equipped with CAN communication possibilities, it was decided to take it to use and only use one single groundable pin to indicate to the AMS that charging takes place. This way the chargers´ hardware does not need to be changed in the near future as the CAN bus will assumedly be in use.

TYPE	CAN SIGNAL	BIT POSITION	BIT SIZE	RX / TX	CYCLUS TIME (MS)	DESCRIPTION
Message	NLG5_CTL	0x618	7	Rx	100	
Bit	NLG5_C_C_EN	0	1	Rx	---	Must be ON to enable power stage of the charger
Bit	NLG5_C_C_EL	1	1	Rx	---	Cycle this value 0-1-0 to clear all latched charger errors
Bit	NLG5_C_CP_V	2	1	Rx	---	Special signal to tell a charging station equipped with the Control pilot interface (SAE J1772) to switch on the facility's ventilation (in order to get rid of battery gases like hydrogen, e.g.)
Bit	NLG5_C_MR	3	1	Rx	---	Enables CP-State C to request mains voltage
Signal	NLG5_MC_MAX	8	16	Rx	---	Maximum current to be drawn from the mains outlet, usually 16 A. Must always contain a valid value in order to keep on charging.
Signal	NLG5_OV_COM	24	16	Rx	---	Desired voltage to be output to the battery. Must always contain a valid value in order to keep on charging.
Signal	NLG5_OC_COM	40	16	Rx	---	Desired battery current. Must always contain a valid value in order to keep on charging.

Figure 22 Required CAN messages for charge control

The chargers are activated only when the charging control connector and the main charging connector are mounted. An interlock prevents the chargers to activate before both connectors are on place, this ensures the safety of the charger. When the charger is active, the charging voltage and current are controlled by the PLC based on the feed-back from the AMS. The specifications for the charging itself are determined based on cell datasheets.

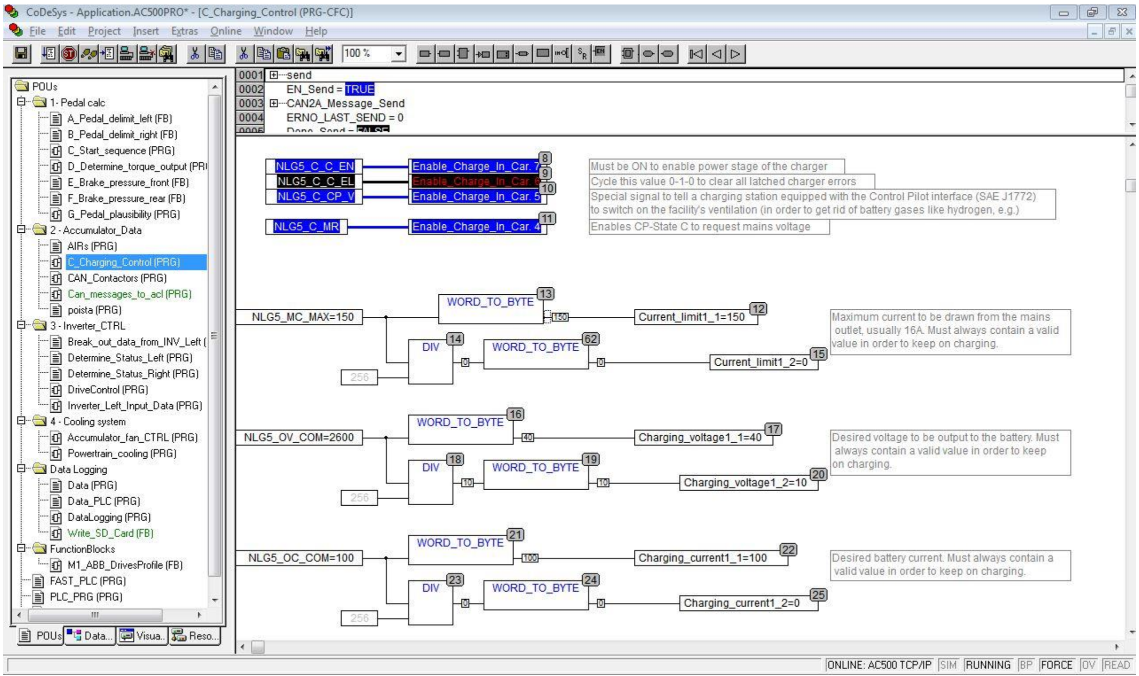

Figure 23 Charging control program has a feedback from AMS to set the correct charging voltage

During August the charging process was fine-tuned to optimize the charging cycle, finally the cell spread is typically between 11mV…25mV when charging is finished. This is considered a good result for the cells used. The cells have now approximately 70 cycles of the manufacturer estimate 300.

8 Field testing and code development

The first field test was carried out on 8 May 2016. The test was made with the intention to try how the control system functions with the inverters and to look for possible flaws in the behaviour of the system. The test drive was approximately 6 km long.

After the test drive the car was placed on trestles for further development. The car was discovered functional but the battery still lacked software for charging, cooling system control and data logging.

After five weeks of further development a second test was conducted with the target to have the car ready for exhibition purposes. At this stage the car already had a working charge system and cooling but it still lacked the data logging possibilities due to a difficulty in the code development. The test drive unfortunately ended short on only around 4 km due to an interference issue from the inverters´ electric field to the AMS, which caused the CRC check to fail on the SPI bus in the accumulator AMS system. This caused the AMS to open the contactors multiple times.

The issue at hand was similar to earlier problems during the competition year and the project was delayed form the original finish from early June to late August to solve the problems keeping the car off the track.

Figure 24 ISOspi spectrum analysis results without interference.

After decoding the live data from the accumulator the CRC check issue was studied. A spectrum analysis was conducted with the help of Metropolia Motorsport ry members to better understand the issue at hand. The physical signal was interfered, which caused the bits to fail. Different options for filtering the signal were considered, and discussed with the importer of the Integrated Circuit (*IC*). However, while studying how distance affects the disturbance it was noticed that a different grounding layout through mounting points to the frame affected the faults. After a few iterations of grounding the CRC check issue was rectified. After the issue had been fixed not one single CRC fault has been identified.

Figure 25 ISOspi spectrum analysis results with interference.

The field testing was continued with several battery cycles to determine the reliability of the system. However, the AMS started to cause unexpected shutdowns of the system. This naturally led the device to open contactors. The issue was rerouted by utilizing CAN bus data to set battery limits, duplicating the DC link voltage reading by sending the data from the inverters and taking a higher layer control of the AMS. All limits are therefore monitored and faults require two of the systems to fail simultaneously. During several drive cycles the limitation functions were tested to be safe.

After this point of modifications, no identified issues with the powertrain have been confirmed. On 15 August the car had been tested for an estimated 140 km, with more than 60 km with no shutdown of the powertrain. The information gained from the tests and measurements are applied to the new competing car with the goal to avoid such issues in the future.

The data logging was introduced on 29 August. The first pieces were gathered before an unofficial competition in Estonia, Põltsamaa, which was the last field test of the car. The competition is organized to compete with second-year FS cars, which are not allowed to compete at official events. The competition lasts for four days and consists of the following events:

Acceleration 125 points

A 75 m acceleration. Time for HPF015 was **4. 28 seconds and placed 4th**

Super slalom 125 points

A significant amount of cones are added to a fast sprint track to make the track profile an unending slalom. The race is a good test for the agility of the car in slow speeds. Time for HPF05 was **23. 19 seconds and placed 1st**

Sprint 250 points

A karting track is slowed down by adding sharpness to the corners with additional cones. Time for HPF05 was
RUN 1 **49. 10 seconds and placed 7th**
RUN 2 **54. 98 seconds and placed 1st**

Endurance 500 points

Endurance is ran for 22 km with one driver change at 11 km allowing 15 minutes of charging time. The event was not participated in, due to a breakdown of the car in the second sprint.

Overall

Position 12 / 15.

The second part of the sprint was run in rainy conditions. The section itself went very well until there was a dielectric breakdown on one of the capacitors of the inverter. The breakdown happened at a static no-load situation and was traced down to be caused by humidity (based on manufacturer statement). The breakdown took two 90 A fuses and some of the inverters´ functionalities with it.

When the competition was finished HPF015 has been driven for 70 battery cycles. In overall this consists of an estimated 770 km of testing, wherefrom, 250 km has been carried out in 2016.

9 Results

The results of the design can be estimated based on the original criteria of the required functions of the system and the documentation generated during the process. The documentation given in the appendices includes the layout of the system, wiring harness pinouts and the schematic.

Additional files including the exact module pinouts and the software are given to Metropolia Motorsport ry in case of future development of the car. Due to the amount of code, it is not possible to include detailed documentation within the appendices but it can be studied with Automation Builder. However, the design phase was considered successful. The issue with the sponsorship was solved and a result was obtained. Unfortunately the schedule did not keep exactly as intended considering the wiring harness design. The final delay after the design was approximately five weeks.

Referring to Chapter *4.1 System Requirements* the most required basic components were fitted to the system. The hardware required by the functions could be mounted to the system as intended and can be put to use by the PLC program when required. Tools for reading data from the buses ca be obtained from ABB. However, the UI will need to be studied to use the system. Some data can also be logged by the system during a drive cycle. A lack of easily changeable limitations is, however, present. Some voltage dividers were not added and the user has therefore only pre-set values in use. The system also lacks several temperature sensors.

The installation of the hardware has endured all testing conditions during this project work. Tests in harsh competition environments have taken place during the Baltic Open 2016 event. However, the system lacks testing in cold environments. According to the design, all expansion possibilities have been left to provide an easy access for any future user. This also comprises the expandability of the harness.

The development of the software and its functions were started two weeks late in comparison to the overall project timeline. The basic functions were finished at an early stage. This allowed the car to do its first test drive on 8 May. However, issues with the use of CAN bus data and data logging slowed down the project significantly. The thesis, that was originally intended to be finished by the end of May, was finished at the end of August.

Finally, the system breakdown during the competitions leaves the car in a condition where it cannot be used in exhibition runs. The failures are, however, clear and can be fixed within a couple of days if new components can be acquired. By doing this the system will be in the intentional condition and the system can be developed further. The actual control system is, however, in usable condition.

The second lack of system development has been in data logging; even though a functional system was introduced, it requires a significant amount of work to create a system which can easily log all possible data from the system. All but some rear unit sensors regarding dynamic system temperatures are present in the data bus.

In addition to the system, documentation was produced to simplify the introduction of the charger with new cars. The storage and instructions for the car are also documented to keep HPF015 in as good a shape as possible to obtain its exhibition value.

10 Conclusions

The use of an industrial PLC in an electric car seems to be a viable option when choosing electrical components for the system. The calculative power and program memory are higher than required in a small car. The expandability would be very usable especially in sedan sized cars. Only noticed fault with the control system was a bug in the ProfiNet units used in the inverters, which was fixed by a software update. All other difficulties were tracked down to the lack of expertise in programming and had very little to do with system issues.

Studying the documentation of the system requires a different approach compared to typical automotive (prototyping) units. The knowledge needed for programming requires prerequisites from CoDeSys in case of rapid prototyping. Even so the possibility to unify the system with higher level protocols and faster data buses can improve the compatibility of the powertrain and control system units used. Since none of these units are yet manufactured for automotive use, the projects utilizing this type of system will be few in numbers.

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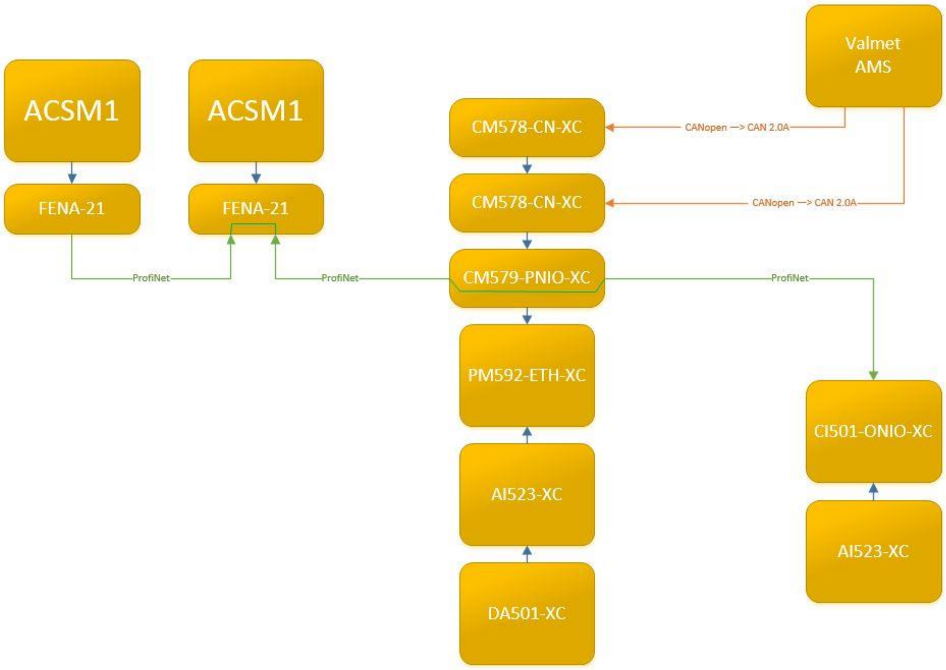
Data bus diagram



Data logging map HPF015

Data logging map HPF015

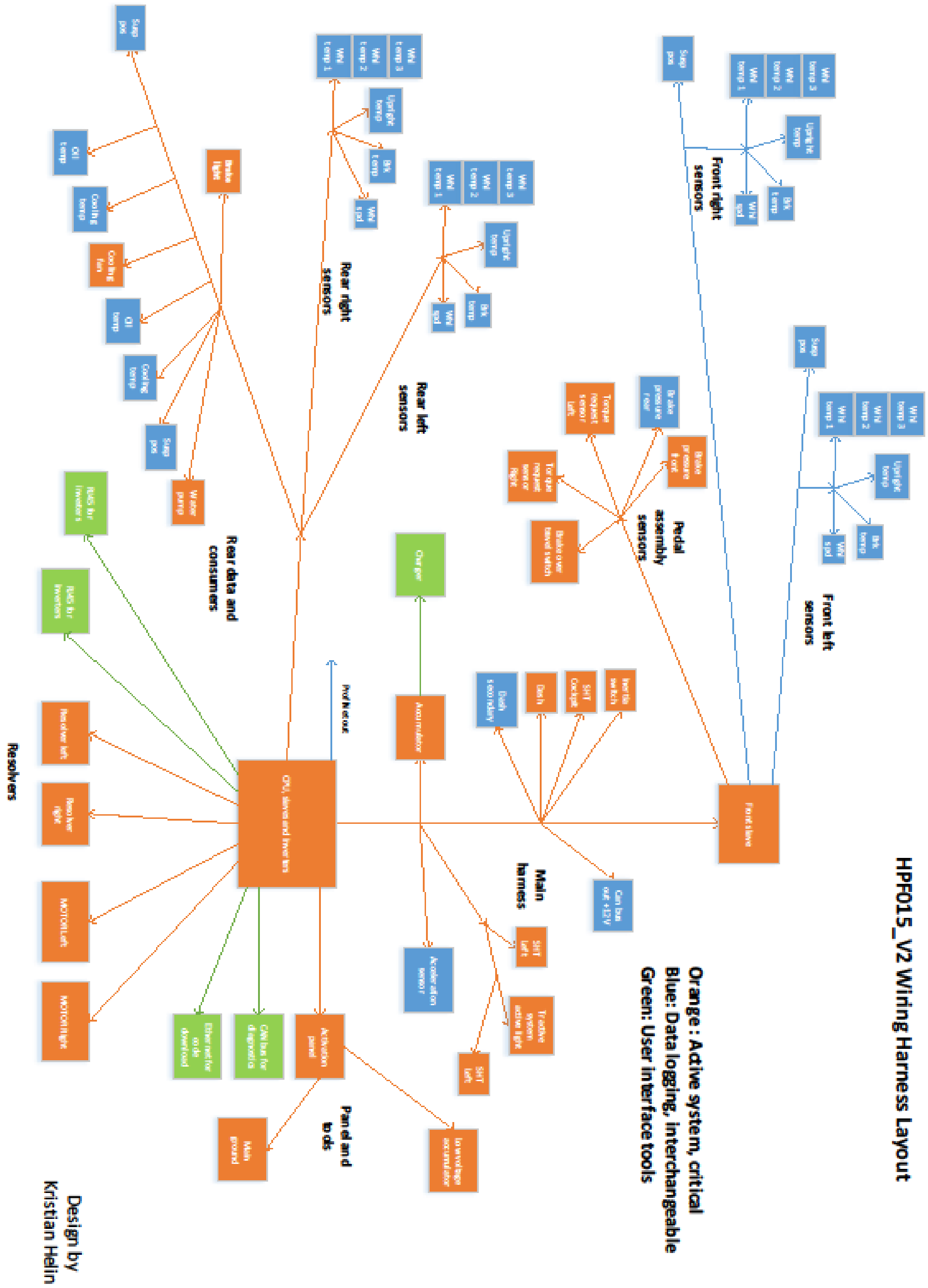
Mixed data

	Quantity	Freq. (Hz)			Sample amount		
		min	average	max	min	average	max
Torque encoders	2	200	200	500	400	400	1000
Brake pressure	2	200	500	1000	400	1000	2000
Steering angle	1	200	200	500	200	200	500
Acceleration sensor	3	200	500	1000	600	1500	3000
Suspension travel	4	500	500	1000	2000	2000	4000
Brake temperature	4	20	20	200	80	80	800
Wheel temperature	12	5	10	100	60	120	1200
Wheel speed	4	50	200	2000	200	800	8000
Powertrain temperatures	4	1	1	10	4	4	40
Digital states	15	1	1	20	15	15	300
Accumulator data							
Battery voltages	140	10	10	100	1400	1400	14000
Battery temperatures	90	5	5	20	450	450	1800
Other accumulator data	15	10	20	100	150	300	1500
Slave board faults calc.	15	50	50	200	750	750	3000
Inverter data							
Active drive data	30	20	100	200	600	3000	6000

Data logging map HPF015

Logging time 5 min...40 min				Data in bits		
min	average	max		min	average	max
300	1200	2400		120000	480000	2400000
300	1200	2400		120000	1200000	4800000
300	1200	2400		60000	240000	1200000
300	1200	2400		180000	1800000	7200000
300	1200	2400		600000	2400000	9600000
300	1200	2400		24000	96000	1920000
300	1200	2400		18000	144000	2880000
300	1200	2400		60000	960000	19200000
300	1200	2400		1200	4800	96000
300	1200	2400		4500	18000	720000
300	1200	2400		420000	1680000	33600000
300	1200	2400		135000	540000	4320000
300	1200	2400		45000	360000	3600000
300	1200	2400		225000	900000	7200000
300	1200	2400		180000	3600000	14400000
		Overall (bits)		2192700	14422800	113136000
		Memory required (Byte)		4385400	28845600	226272000
		Memory required (MB)		4,282617	28,16953	220,96875

Appendix 3. Wiring harness layout



[***Wiring harness layout***]()

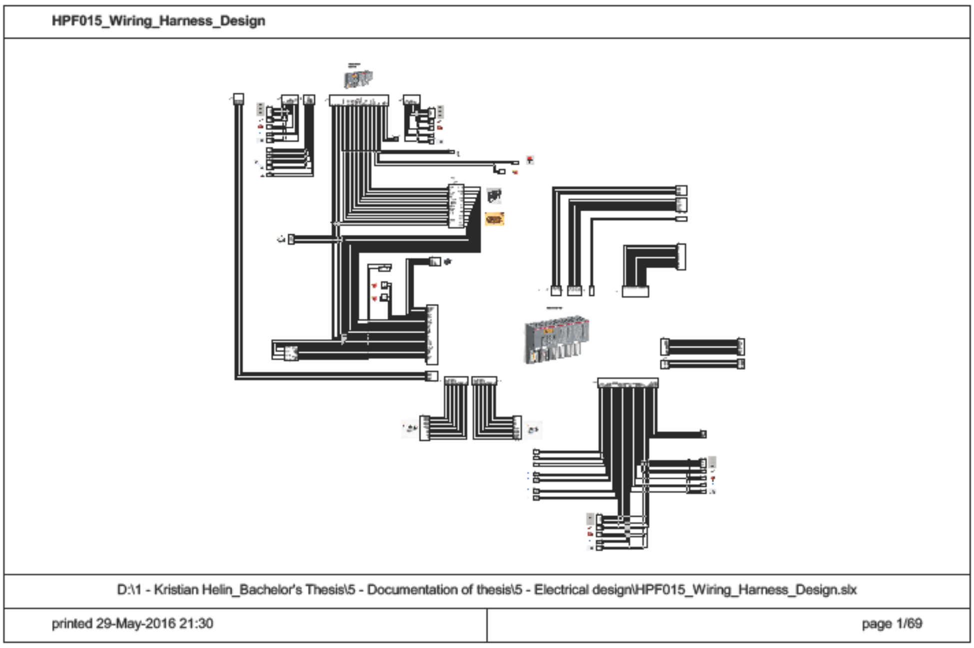
Appendix 4. Current calculations

Hardware current c	Avg.	V [U]	*	I [A]	P [W]	Utilization	Max P
AC500 VCU unit	0,150	24	1	0,150	3,600	100,00 %	3,600
CI501-PNIO-XC	0,560	24	1	0,560	13,440	100,00 %	13,440
AI523-XC	0,150	24	2	0,300	7,200	100,00 %	7,200
CM578-XC	0,050	24	1	0,050	1,200	100,00 %	1,200
DA501-XC	0,570	24	1	0,570	13,680	100,00 %	13,680
CM579-PNIO	0,150	24	1	0,150	3,600	100,00 %	3,600
ACSM1	1,600	24	2	3,200	76,800	100,00 %	76,800
FENA 21	0,150	24	2	0,300	7,200	100,00 %	7,200
Fan	0,050	24	2	0,100	2,400	68,00 %	1,632
IMD	0,150	24	1	0,150	3,600	100,00 %	3,600
AMS	2,000	24	1	2,000	48,000	100,00 %	48,000
Accumulator spare	0,200	24	1	0,200	4,800	70,00 %	3,360
Fan	0,150	24	2	0,300	7,200	85,00 %	6,120
AIR's	0,150	12	2	0,300	3,600	100,00 %	3,600
Energy meter	0,300	24	1	0,300	7,200	20,00 %	1,440
BSPD	0,200	12	1	0,200	2,400	15,00 %	0,360
Buzzer	0,200	12	2	0,400	4,800	4,00 %	0,192
Waterpump	3,800	12	1	3,800	45,600	40,00 %	18,240
Fan	3,600	12	1	3,600	43,200	45,00 %	19,440
Brake light	2,2	12	1	2,200	26,400	5,00 %	1,320
	0,350	24	1	0,350	8,400	35,00 %	2,940
Wheel speed	0,003	24	4	0,012	0,288	100,00 %	0,288
Torque encoder	0,020	24	2	0,040	0,960	100,00 %	0,960
Brake pressure	0,010	5	2	0,020	0,100	100,00 %	0,100
Steering angle	0,014	5	1	0,014	0,070	100,00 %	0,070
Suspension travel	0,010	5	4	0,040	0,200	80,00 %	0,160
Acceleration	0,010	5	3	0,030	0,150	100,00 %	0,150
Brake temp	0,010	5	4	0,040	0,200	40,00 %	0,080
Upright temp	0,070	5	4	0,280	1,400	40,00 %	0,560
Wheel temp	0,010	5	12	0,120	0,600	40,00 %	0,240
Telemetry freq setting.	0,008	5	1	0,008	0,040	80,00 %	0,032
Telemetry system setting	0,008	5	1	0,008	0,040	80,00 %	0,032
Maximum sped pot	0,010	5	1	0,010	0,050	80,00 %	0,040
Maximum torq spd	0,010	5	1	0,010	0,050	80,00 %	0,040
Steering wheel	0,010	5	4	0,040	0,200	100,00 %	0,200
Coolant temp	0,010	5	2	0,020	0,100	100,00 %	0,100
Powertrain oil temp	0,010	5	2	0,020	0,100	100,00 %	0,100
Yaw sensor	0,130	12	1	0,130	1,560	100,00 %	1,560

Sht cockpit	0,005	10	1	0,005	0,050	100,00 %	0,050
Data log activation	0,005	10	1	0,005	0,050	100,00 %	0,050
RTDM switch	0,005	10	1	0,005	0,050	100,00 %	0,050
TS Switch	0,005	10	1	0,005	0,050	100,00 %	0,050
CS switch	0,005	10	1	0,005	0,050	100,00 %	0,050
BOTS	0,005	10	1	0,005	0,050	100,00 %	0,050
Inertia switch	0,005	10	1	0,005	0,050	100,00 %	0,050
Wild mistress	0,005	10	1	0,005	0,050	100,00 %	0,050
Str wheel +	0,005	10	1	0,005	0,050	100,00 %	0,050
Str wheel -	0,005	10	1	0,005	0,050	100,00 %	0,050
Launch ctrl.	0,005	10	1	0,005	0,050	100,00 %	0,050
TS off	0,005	10	1	0,005	0,050	100,00 %	0,050
RTDM off	0,005	10	1	0,005	0,050	100,00 %	0,050
Problem marker	0,005	10	1	0,005	0,050	100,00 %	0,050
Discharge state	0,005	10	1	0,005	0,050	100,00 %	0,050
TSAL state	0,005	10	1	0,005	0,050	100,00 %	0,050
SHT button right	0,005	10	1	0,005	0,050	100,00 %	0,050
SHT button left	0,005	10	1	0,005	0,050	100,00 %	0,050
IMD State	0,005	10	1	0,005	0,050	100,00 %	0,050
Reset AMS	0,005	10	1	0,005	0,050	100,00 %	0,050
Reset IMD	0,005	10	1	0,005	0,050	100,00 %	0,050
Acceleration	0,005	10	1	0,005	0,050	100,00 %	0,050
Endurance	0,005	10	1	0,005	0,050	100,00 %	0,050
Skid pad	0,005	10	1	0,005	0,050	100,00 %	0,050
Autocross	0,005	10	1	0,005	0,050	100,00 %	0,050
General Fault	0,010	10	1	0,010	0,100	20,00 %	0,020
RTDM active	0,010	10	1	0,010	0,100	97,00 %	0,097
TS active	0,010	10	1	0,010	0,100	95,00 %	0,095
CS active	0,010	10	1	0,010	0,100	95,00 %	0,095
AMS fault	0,010	10	1	0,010	0,100	10,00 %	0,010
IMD fault	0,010	10	1	0,010	0,100	10,00 %	0,010
Fault code 1	0,005	10	1	0,005	0,050	30,00 %	0,015
Fault code 2	0,005	10	1	0,005	0,050	30,00 %	0,015
Fault code 3	0,005	10	1	0,005	0,050	30,00 %	0,015
Fault code 4	0,005	10	1	0,005	0,050	30,00 %	0,015
Fault code 5	0,005	10	1	0,005	0,050	30,00 %	0,015
ZigBee	0,04	24	1	0,040	0,960	20,00 %	0,192
Xbee	0,045	24	1	0,045	1,080	15,00 %	0,162
GPS	0,2	24	1	0,200	4,800	15,00 %	0,720
Radio	0,15	24	1	0,150	3,600	20,00 %	0,720
Display	0,1	24	1	0,100	2,400	100,00 %	2,400
Dash additional value	1	24	1	1,000	24,000	25,00 %	6,000

	Consumption maximum	Consumption avg
Overall values	**379,368 W**	
Drive with nom. power consumption	253,522 W	**253,522 W**
Drive with max. power consumption	379,368 W	
Cell capacity	23,68 Wh	
Cells in stack	7 qty	
Stacks	3 qty	
Ulitizable capacity of LV battery	0,7 factor	
Usable capacity	348,096 Wh	
Percentage of hour	0,91757 factor	
Percentage of hour	1,37304 factor	
Time	60 min	
Time to drive with max power consumption	55,0541 min	
Time to drive with nom power consumption	82,3824 min	

Appendix 5. HPF015 Wiring Harness Design.pdf



[HPF015 Wiring Harness Design]()